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APPENDIX

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АТОМНОЕ ЯДРО

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Chapter I

RADIOACTIVITY

Becquerel's Discovery

In 1912, the eminent British scientist Rutherford succeeded for the first time in obtaining convincing evidence that atomic nuclei really exist. However, the history of our knowledge concerning atomic nuclei begins earlier.

The nuclear chronicle should actually begin with 1896. This starting point was marked by a scientific error, or, to be more precise, by an incorrect scientific hypothesis.

The question at hand concerned the nature of the then mysterious X-rays discovered just before (1895) by the German scientist Roentgen. Men of science in all countries were then under the impression of this discovery. Roentgen's work was subjected to careful study and discussion. The French scientist Henri Becquerel took note of Roentgen's remark that the invisible X-rays he had discovered emerge from the end of a glass tube that glows with a yellowish green light which resembles the light of fluorescent substances. Both the yellowish green glow and the X-rays come out of the same spot of the glass tube. This was not fortuitous. In the tube with which Roentgen performed his investigations, the production of X-rays was always accompanied by a yellowish green illumination of the glass.

Becquerel had spent a long time in the study of various fluorescent materials which under the action of sunlight begin to radiate their own peculiar light.

The idea that stimulated Becquerel's experiments was simple: is not fluorescence the cause of X-rays? Maybe X-rays exist whenever there is fluorescence? Now, in the light of our knowledge concerning the constitution of the atom and the nature of X-rays, this idea seems absurd, but at

that time when the nature of these rays was unknown, this assumption appeared quite natural.

Becquerel was, of course, just lucky. It was by sheer accident that for the fluorescent material he took one of the uranium salts, the double sulphate of uranium and potassium. This circumstance predetermined the success of the experiment which was extremely simple and amounted to the following.

A photographic plate was carefully wrapped in black paper that did not pass visible rays. Then the uranium potassium sulphate was placed on the paper. The plate was then placed in bright sunlight. Several hours later it was developed with all possible precaution. A dark spot was detected on the plate and in form resembled the silhouette of the fluorescent material. Becquerel performed a series of control experiments and showed that this darkening arose from the action on the photographic plate of rays coming from the uranium crystals and passing through the black paper that is impenetrable to the sun's light.

At first Becquerel did not doubt that these were the X-rays. But he soon saw that he was mistaken.

During these experiments, one of the days happened to be overcast and the uranium salt was hardly at all fluorescent. Assuming the experiment to be unsuccessful, he put the plate with the uranium salt back into the drawer of the case where it remained several days. Before his next experiment he developed this plate since he was not sure that it was good any longer. To his surprise he saw a dark spot on the plate that was the image of the salt; the intensity of this image was exceptionally great. But in the dark case the salt had not fluoresced. Hence, fluorescence had nothing to do with it: there was something that affected the plate without fluorescence.

It was obvious that Becquerel had encountered some kind of new rays, and very soon it was established that these rays were due to *uranium*. Only such fluorescent materials as contained uranium affected a photographic plate, and a plate was affected by any of the uranium salts. But the strongest action was that produced by uranium itself.

The rays discovered by Becquerel resemble to some extent Roentgen's rays. *They act on a photographic plate,*

and pass through black paper and thin layers of metal. However, these rays differ greatly. X-rays arise during an electric discharge in a highly rarefied gas. The pressure of the gas must be of the order of a millionth part of atmospheric pressure. A very high voltage (hundreds of times greater than the 110 volts that we are accustomed to in everyday life) must be applied to the electrodes before a discharge takes place. In these conditions, the X-rays are produced regardless of the nature of the gas in the X-ray tube and also of the substance of the electrodes.

Becquerel's rays do not require any electric potential, either large or small. And no rarefied gas is necessary. X-rays appear only in the presence of an electric discharge, while Becquerel's rays radiate continuously and at all times. However, they are emitted only by uranium. But is uranium the only substance? This was the question that Marie Sklodowska Curie asked.

Marie Curie's search was long and incredibly difficult. It lasted nearly two years, during which time a tremendous number of different salts, minerals, and ore rocks were studied. But at last Curie succeeded. It was found that thorium salts also emit Becquerel rays. Just as in the case with uranium, it appeared that the more thorium the substance contained the greater the intensity of these rays, and that, when compared with its compounds, pure thorium is distinguished by the greatest intensity of radiation.

In the search for substances that emit Becquerel rays, Curie did not employ photographic plates. She made use of another remarkable property (discovered by Becquerel) of these rays.

In his first experiments Becquerel noticed that due to the action of the rays emitted by uranium *the air becomes a conductor of electricity.* This remarkable property of the Becquerel rays greatly simplified the search for substances that radiate them.

The test is very simple. An electroscope—an instrument that measures electric charges — is charged. When this is done, the leaves that are attached to a metal rod repulse one another and diverge at an angle that increases with the magnitude of the charge received by the electroscope. The leaves will remain in this position as long as the charge

is retained on the rod of the instrument. But the charge will be retained only if the leaves are well insulated from the body. Air, as we know, is a good insulator, and therefore the leaves usually retain their position a rather long time, but if one puts some uranium or its salts in the electroscope it will quickly discharge, and the leaves will fall together. In this way, it takes two or three minutes to establish whether the substance under study is emitting Becquerel rays or not (it is noteworthy that this simple method of detecting substances emitting Becquerel rays is still used).

Continuing her search, Curie came upon a surprising fact. It turned out that pitch-blende, the ore from which metallic uranium is extracted, emits Becquerel rays with an intensity that far exceeds that of pure uranium. It became clear that there was some sort of new substance in pitch-blende (in the form of an admixture) that is capable of emitting these Becquerel rays very intensively, because the tiny admixture of this substance that had escaped the attention of chemists radiated more strongly than uranium, of which there was an incomparably greater quantity in the ore. In the long and laborious search, Marie Curie, working together with her husband Pierre Curie, succeeded in isolating two new substances—the carriers of the Becquerel radiation. *Radioactive* was the name given by M. Curie to all substances capable of radiating the Becquerel rays. It means capable of emitting rays. The phenomenon itself—the emission of such rays—came to be known as *radioactivity*. Later, the rays discovered by Becquerel began to be called *radioactive* rays.

The two new substances discovered by Curie were not to be found among the known chemical elements (uranium and thorium had been known long before Becquerel's discovery). These were new elements. One of them was called polonium (in honour of Poland, M. Sklodowska Curie's native country). The other radioactive element, with chemical properties resembling those of barium, was called radium.

The discovery of radium was a great event. In importance it may easily be placed alongside the discovery of the Becquerel and Roentgen rays. Radium was found to radiate with an intensity one million times that of uranium.

This quantitative difference led to consequences of extraordinary significance. The very power of the radium radiation made it possible to detect many new properties of radioactive rays, some of which were soon to find practical application.

The Properties of Radioactive Radiation

Becquerel once borrowed from Pierre Curie a small amount of a radium preparation in a glass tube to demonstrate its properties to his students at a lecture. He put the tube with the radium in his vest coat pocket and went about with it for several hours. Some days later he noticed that the skin on his body opposite the pocket where the radium had been was all red, and the redness covered a spot just the size of the tube of radium. Several days after this, Becquerel felt severe pain, the skin began to crack and a sore formed. He had to go to a doctor. The wound was treated in the same way as ordinary burns, and about two months later it healed.

Pierre Curie experimented on himself in order to check the action of radium rays that Becquerel had told him about. The facts were confirmed. A ten-hour irradiation of the skin on his hand by a preparation of radium led, several days later, to the very same results: redness, inflammation, and an open wound that required four months to heal.

Doctors became interested in Curie's experiments and began a systematic study of the action of radium rays on animals, and later on humans. It was soon found that weak doses of radium rays are capable, in certain cases, of affecting the organism favourably. For example, they cured different skin diseases very well.

After the results of these experiments became known, there began a widespread study of the medical and biological action of radium rays. A little while later it was noticed that radium rays act differently on different cells and tissues. Cells that multiply rapidly are most readily destroyed by the action of radium rays. This outstanding discovery immediately determined the practical value of these rays. Radium became an invaluable aid to physicians in their fight against cancer, that scourge of humanity.

A malignant tumour consists of extremely rapidly multiplying cells, therefore the rays of radium act on it much more destructively than on the normal healthy tissues. Radium treatment is done as follows: the preparation of radium, in a gold case, is placed as close as possible to the tumour; irradiation continues a certain length of time. If the disease has not been neglected and if the tumour is not too far inside the organism, treatment is quite successful and rapid.

Another property of the radium rays, and one that also found a practical application, was noticed immediately after the first strong preparations were obtained.

It appeared that radium rays, just as the sun's rays, are capable of exciting fluorescence in fluorescent materials. Veritably microscopic quantities of radium make screens of zinc sulphide, barium platinocyanide, and other similar substances glow brightly in the dark.

By adding minute quantities of radium to zinc sulphide we obtain a compound that is continuously luminous in the dark. This was made use of, for example, in the production of watches with luminous dials. During the First World War, a luminescent substance was used on gun sights so that the soldiers could aim in the dark. It is often used to coat pointers and divisions on instruments to make them readable in the dark. Luminescent substances are now in use also in many technical fields and in warfare.

The Energy Radiated by Radium

Fluorescent materials emit light only after illumination by sunlight. If such substances are protected from the action of the sun's light they stop being luminous.

When it was established that the rays of radium also cause fluorescence, scientists noticed at once that the situation was very peculiar. A grain of radium added, for example, to zinc sulphide makes it constantly fluorescent. Observations continued day and night, week in and week out, and over months and into the years, but the zinc sulphide continued to fluoresce without any noticeable diminution in the intensity of the light emitted. A highly para-

doxical result! If fluorescence is caused by radioactive rays, then radium emits these rays without any visible decrease in intensity *continuously* and for an indefinitely long time.

Now how can this be? These rays must possess energy as all other rays do. And does not this mean that radium is constantly radiating energy? The answer to this question was given by Pierre Curie.

Soon after obtaining strong preparations of radium he noticed that the substance containing radium was always warmer than the surrounding objects. He decided to make use of this fact to measure the energy liberated by radium. He took a calorimeter (an instrument commonly used to measure thermal energy) with walls thick enough for the radioactive rays to be absorbed entirely in them and in the ice with which it was filled. Since by that time experimental data on the absorption of radioactive rays by various bodies were sufficiently well known, a calorimeter of this type could easily be designed. The amount of energy liberated by the radium could be judged by the quantity of melted ice. Knowing how much heat is required to melt one gram of ice (melting heat) and the weight of the melted ice, it is possible to determine how much heat is liberated by a given quantity of radium during the period of the experiment. It is then a simple matter to calculate the energy liberated by one gram of radium per second.

From these measurements, Curie found that one gram of radium liberates in one hour 140 calories, which is not a very large energy (it may be recalled that one calorie is that amount of heat capable of heating one gram of water one degree Centigrade). Thus, the energy liberated by radium is so small that the amount required to heat one glass of water to boiling is liberated by one gram of radium only in six days.

The energy released by radium in one hour is small. But it is released continuously during a very long period of time. Consequently, the total amount of energy liberated by radium is great. The natural question is, where does radium get all this energy?

One of the basic laws of physics is the law of conservation and transformation of energy. This law was estab-

lished on the basis of observations and investigations and embraces and summarizes all the facts known to science.

According to this law *energy is neither created nor destroyed; energy may only be transformed from one form into another.*

The energy of radioactive substances is released in the form of radioactive rays. It should be noted that this goes on continuously. At first, workers were unable to connect the liberation of energy with any changes in the radioactive substances themselves. The supply of this energy in radioactive substances seemed limitless.

The difficulty that arose in the study of radiation by radium was made worse by other discovered facts.

Quite naturally, when we wish to study a phenomenon our task is to find the forces of nature that affect this phenomenon, to find those things that are capable of changing its character. When those forces are found it is easier to map out the route to be traversed so as to connect the phenomena at hand with other familiar phenomena. Here investigators did not meet success either. They were unable to find any means capable of influencing the radioactive power of radium. High and low temperatures were tried, strong electric and magnetic fields were applied, tremendous pressures, and the strongest possible chemical reagents were put to use, but not a single one of the most powerful weapons of the physical laboratories affected the radiation of energy by radium.

At the beginning of this century the word radium was spoken of by many. The riddle of radioactivity was spurring workers in all fields, and especially physicists; and nearly all of them were endeavouring to find an explanation of these apparently mysterious facts. There was only one thing to be done—study the properties of radioactive rays and search for traces of changes taking place in radium. But how was one to seek them?

In the effort to decipher the secret of radioactivity, men of science struck out in different directions and the results of their titanic creative endeavours were not long in telling.

where g_E is the acceleration of the particle in an electric field, and E is the electrical field strength.

If the distance in the electric field is l, the speed of the particle u, then the time during which it will pass through the electric field will be:

$$t=\frac{l}{u}.$$

By substituting the obtained values of g_E and t into the expression for s, we will find that the particle in covering the distance l in the electric field will experience a displacement of s_E:

$$s_E=\frac{1}{2}\frac{eE}{m}\left(\frac{l}{u}\right)^2. \qquad (1)$$

Thus, it comes out that the displacement of a charged particle in an electric field depends both on known values, the distance l and the electric field strength E, and on unknown values, the speed of the particle u and the ratio of the magnitude of its charge e to the mass m. However, since we do not know the speed of an alpha particle even if we measured the deflection of these particles in an electric field we would not be able to determine the ratio $\frac{e}{m}$, but would determine only the product $\frac{e}{m}\times\frac{l}{u^2}$. But if the charged particle moves not only in an electric field but also in a magnetic field, it will experience two displacements: one from the action of the electric force, and the other from the magnetic force. The magnetic force acting on the particle depends not only on the magnitude of the charge and the magnetic intensity but also on the velocity of the particle. Acceleration in a magnetic field g_H is equal to:

$$g_H=\frac{eHu}{m},$$

where H is the magnetic intensity, and the other letters are the same values as in the preceding case.

The displacement experienced by a particle which covers a small distance l in a magnetic field H, is equal to:

$$s_H=\frac{1}{2}\frac{eHu}{m}\left(\frac{l}{u}\right)^2=\frac{1}{2}\frac{eHl^2}{mu}. \qquad (2)$$

Although the deflection in the magnetic field is also dependent upon the speed of the particle and the ratio $\frac{e}{m}$, this dependence differs from that found in the case of an electric field. The deflection is determined by the ratio $\frac{e}{mu}$, that is, it depends not on the kinetic energy of the particle as in the case of the electric field, but on the momentum mu of the particle. Using the two equations for s_H and s_E, each of which contains two unknowns $\frac{e}{m}$ and u, it is possible to determine both.

That is exactly what Rutherford did. The result of his measurements was: $\frac{e}{m}=1.44\times10^{14}$ electrostatic units per gram (3), and the greatest velocity u was 19,000 km. per second. This is a tremendous speed, but still it is from 10 to 15 times less than that of the electrons of beta rays.

It may be recalled that for electrons the ratio of charge to mass $\frac{e}{m}$ was found to be 5.3×10^{17} electrostatic units per gram.

A comparison of the ratio $\frac{e}{m}$ for electrons with the value $\frac{e}{m}$ obtained by Rutherford for alpha particles shows that the ratio $\frac{e}{m}$ for alpha particles is roughly 3,600 times less than for electrons.

Since we do not know of any charge that is less than that of a single electron, from the above-stated fact it follows that the mass of an alpha particle is several thousands of times that of an electron; in other words, the mass of an alpha particle is of the same order as that of individual atoms.

The earlier measured ratio $\frac{e}{m}$ for hydrogen ions is equal to 2.89×10^{14} electrostatic units per gram, which is twice that of the alpha particles. A correlation of all these values led Rutherford to the natural conclusion that the mass of an alpha particle is of the same order as the mass of an atom of hydrogen or close to it, and that consequently an alpha

particle may be an ion of some unknown substance. But what substance?

If the charge of an alpha particle were the equivalent of one elementary charge,* the mass of the alpha particle would be twice as large as the mass of a hydrogen atom. But in those days no such element was known with an atomic mass twice that of an atom of hydrogen. It could, of course, be that the alpha particles were really ionized atoms of some unknown element, but Rutherford surmised otherwise. He assumed that the charge of an alpha particle was not equal to the charge of an electron, but greater, and therefore its mass must also be heavier than that of a hydrogen atom not by a factor of two, but more. If we take the charge of an electron as a unit and consider that the charge of an alpha particle is equal to two, then its mass must come to four. In this case the alpha particle could be a doubly ionized atom of helium (that is, one minus two electrons), but if the alpha particle carried a charge of say six units, then its mass would have to be twelve times that of an atom of hydrogen, in which case the alpha particle could be compared with a sextuply ionized atom of carbon.

Rutherford and Soddy advanced the following hypothesis: alpha particles are atoms of helium with two electrons detached, thus producing a positive charge of two units, the ratio of the charge to the mass becoming 1.44×10^{14} electrostatic units per gram.

They saw their hypothesis corroborated in a well-known but hitherto unexplained fact. All minerals containing radioactive substances always contained helium as well. This rule was without exception. It seemed strange that helium (a gas chemically absolutely inert) always accompanied radioactive substances, whereas it was never found in any other minerals. One could be safe in saying that if helium was found in some mineral, then radioactive substances were sure to be present.

Rutherford and Soddy gave this fact a natural explanation: helium does not get into minerals containing radioactive substances from outside; it is formed within them

* The numerical value of the charge of an electron is called an elementary charge.

because radioactive substances emit rays that in part are atoms of helium (doubly ionized). This hypothesis was of exceptional significance. Since the time of Lavoisier and Dalton scientists had considered the chemical elements eternal and immutable; they were never destroyed, never created anew and could never pass from one into another. The only thing possible was their combination in different ways to create all the diversity of the world that surrounds us. Undoubtedly, from Lavoisier's viewpoint (the immutability of the chemical elements) uranium and thorium, and also polonium and radium, that were constantly emitting radioactive rays, behaved very strangely. However, this was no direct contradiction to the views of Lavoisier, for not the slightest changes in radium or in the other radioactive elements could be found. Still, the hypothesis of Rutherford and Soddy put into question the basic conclusion of Lavoisier and Dalton. For did not this hypothesis require that the *chemical element of helium be born* (in the form of radioactive rays) somewhere inside of radioactive substances. To make such a revolutionary contention in science one of course needed facts that were more solid than those at the disposal of Rutherford and Soddy. And these facts were not long in the seeking.

Radium Emanation (Radon)

As early as 1900 Pierre and Marie Curie noticed that the air about radium becomes radioactive, i. e., it begins to emit radioactive rays. However, they did not give an explanation to this strange phenomenon, and the meaning of it escaped them. Rutherford and Soddy unravelled this puzzle too.

Their experiment was simplicity itself both in principle and in execution. They made use of the ability of radioactive substances to cause fluorescence. In order to investigate separately the radioactive properties of air that has been for some time close to radium, they took a glass tube with two cocks, one at each end. In this way one could isolate the air inside the tube from outside effects. Then they put inside several pieces of the mineral willem-

ite that fluoresces very well under the action of radium rays. That was all that was needed in the way of apparatus.

And the experiment itself was extremely simple. A certain amount of air that had been in contact with radium for a long time was passed into the tube; both cocks were closed and the tube was taken into another room far removed from the radium. Despite the fact that there was now no radium, the willemite glowed brightly. The brilliance was just the same as when it was in the immediate vicinity of radium. Soddy describes the light coming from the willemite as being so strong that he could read the headlines of a newspaper and tell the time by his watch. However, when

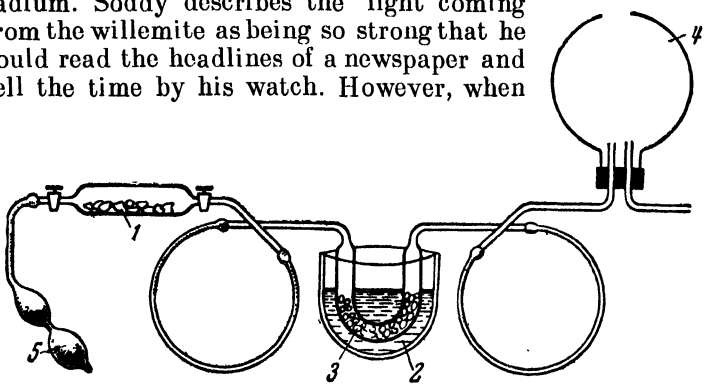


Fig. 2. Rutherford-Soddy experiment.

1 — tube containing willemite filled with radium emanation; *2* — vessel with liquid air; *3* — U-shaped tube for freezing radium emanation; *4* — flask coated inside with zinc sulphide; *5* — rubber syringe used to pump emanation air into flask.

the air was let out of the tube the willemite ceased to luminesce. Rutherford understood that radium was all the time emitting some sort of radioactive gas, which he called "radium emanation." His guess was doubted by many, and it was no easy job for him to prove his point.

In order to prove that radium emanation was an ordinary gas, Rutherford and Soddy decided to turn it into a liquid. To do this, they connected the tube containing the radium emanation and pieces of willemite with a tank coated inside with zinc sulphide, which is also capable of luminescing under the action of radioactive rays (Fig. 2). A U-shaped tube was inserted between the tube with the willemite and

the vessel with zinc sulphide. The U-tube could be cooled to 190° below zero by immersion in liquid air. With the U-tube in liquid air, they began to blow through it the air containing the emanation. But no matter how much theyblew, the zinc sulphide in the vessel did not glow. The emanation did not reach it because it was all stopped in the U-tube. The willemite in the tube luminesced while the zinc sulphide in the flask did not. However, one had only to take the U-tube out of the liquid air and warm it up for the zinc sulphide to begin immediately to glow. Thus, radium emanation could be liquified by cooling and could be again turned into a gas by heating. Hence, it is an ordinary, though radioactive, gas, and not some sort of state intermediate between common matter and the rays of light, as Pierre and Marie Curie had supposed.

Rutherford and Soddy very soon encountered one more very interesting fact. The aim of one of their experiments was to determine what happens to the emanation in the course of time. The experiment was simple. They filled a tube with air that had been close to radium, which, as we already know, contains radium emanation; then they closed the cocks and observed from time to time what happened. The observation was conducted by the luminescence of the willemite (the tube was in the dark). Several days later they noticed that the intensity of luminescence of the willemite had fallen off. By the end of a month it had ceased altogether.

The results of this simple experiment were of exceptional importance because this was the first case when a radioactive substance had lost, after a lapse of time, its ability to emit radioactive rays.

The experiments of Rutherford and Soddy showed that radium emanation disappears in time. The question then arose: into what is it transformed? The answer was found in the work of Ramsay and Soddy.

To study the transformations of radium emanation, these workers decided to make a spectral analysis, which consists in the following. If an electric current is passed through a tube containing the rarefied gas under investigation, it will begin to luminesce, and the colour of this luminescence will depend on the type of gas. If an analysis is made

of this gas in a spectroscope, it will be seen that it consists of individual lines that correspond to definite simple (monochromatic) colours. The totality of these lines make up what is called the spectrum.

The spectra of different gases differ. In the spectrum of each gas there are lines that are specific only to the given gas. By determining in the spectroscope which lines appear, it is possible to establish the gas at hand. This was the method of spectral analysis that Ramsay and Soddy decided to use in studying the emanation.

They filled a spectroscopic tube (a glass tube with two electrodes soldered in it and with a very narrow central part) with air that contained radium emanation, then sealed it and began to observe the luminescence of the gas.

Besides the familiar lines that belonged to nitrogen and oxygen, that is, gases found in the air, they detected hitherto unknown bright lines, which it was natural to attribute to radium emanation. They carried on day-to-day observations of the luminescence in the spectroscopic tube and soon noticed that the luminescence intensity of the lines that belong to the emanation gradually diminished. This was in full accord with the experiments of Rutherford and Soddy who had already proved that radium emanation disappears in time. However, Ramsay and Soddy noted a new fact. It was found that as the intensity of the lines belonging to the emanation attenuates, new lines appear in the spectrum of the luminescing gas. The weaker the intensity of the emanation lines became, the brighter did the new lines glow. And especially remarkable was the fact that these new lines coincided with the very familiar lines of the gas helium. The radium emanation transformed into another gas (helium) before the very eyes of the astonished investigators.

The description of these experiments has brought us back to helium again. Recall now that when Rutherford studied the radioactive rays emitted by radium, he had supposed that alpha rays were the doubly ionized atoms of helium, and when Ramsay and Soddy saw with their own eyes helium arise from the radium emanation, Rutherford and Royds performed the culminating experiment which showed

with finality that alpha rays are nothing other than helium atoms.

This was the experiment. Rutherford and Royds placed a certain quantity of emanation in a glass tube which was so thin-walled that even the strongly absorbed alpha rays could penetrate it freely. This thin tube was then placed inside a large vessel connected with the spectral tube. The air was then pumped out of this vessel and, hence, also out of the spectral tube connected to it. This was done as thoroughly as the technology of that time permitted. The evacuation was so perfect that when a potential was applied to the spectral tube, no current passed through it and it was impossible to notice even the slightest luminescence.

Two days later when already a goodly number of alpha particles, which Rutherford surmised to be ions of helium atoms, could have penetrated the thin walls of the tube that contained radium emanation, a voltage was again applied to the electrodes of the spectral tube. But this time current passed through the tube and the gas in it glowed brightly. The spectroscope showed a bright yellow line, characteristic of helium, and several days later there began to appear other,weaker lines of the helium spectrum. Rutherford's hypothesis was brilliantly confirmed. The origin of helium from radium and radium emanation was a fact.

After the experiments of Rutherford and Royds and also Ramsay and Soddy it became apparent that Lavoisier's teaching of the immutability of the chemical elements was not exact: in Rutherford's experiments the chemical element of helium arose from the chemical element of radium. Furthermore, helium arose also from radium emanation, the nature of which, by the way, had not been very exactly established. Could it not be that the radium emanation is also a chemical element?

This was what Rutherford and Soddy supposed. They believed that radium emanation, just as helium atoms, arises from radium as a result of the transformation of its atoms. But this is not all. They expressed a still more general hypothesis.

The role of the Geiger-Müller counter in investigations of atomic nuclei is extraordinarily great. It may be compared with the role of the analytical balance in chemical analysis.

The Cloud Chamber

A still more remarkable tool was a chamber devised by C.T.R. Wilson in 1912. Like Geiger, Wilson used the property of alpha particles to ionize air or other gas through which they (the alpha particles) pass, but his approach was quite different.

Being engaged for a long time in the study of conditions of condensation of vapours, he found that water vapour (and also all other vapours, for example, those of alcohol) readily condenses forming a clearly visible fog if the air in which it is present contains a large number of dust particles. Of course, condensation of the vapours takes place only when the requisite physical conditions are observed, that is when the vapours are supersaturated. Supersaturation is achieved by cooling. If, for example, the gas in a tube with a piston is suddenly expanded, it will cool due to the sharp increase in volume, and if prior to expansion it contained a saturated vapour, then after expansion it will become supersaturated, and a fog will begin to form.

However, fog formation will take place only if the air contains dust particles which, as Wilson pointed out, are the condensation nuclei of the vapour.

Later he noted that electric charges can also serve as centres of condensation. If all dust particles are carefully removed from the air, and if ions are produced, then condensation will take place on the ions. Around each ion there will form a tiny droplet of liquid.These well-known facts were the basis of his apparatus which enables one not only to count individual alpha particles, but also to see their paths. The principle behind his instrument is as follows.

If a beam of alpha particles is let into a chamber containing water vapour, the alpha particles will, in moving through the vapour, produce ions. And the number of

ions, as we know, will be very great. On each centimetre of path alpha particles form several tens of thousands of ions. If now we suddenly increase the volume of air in the chamber, the air will cool and, as was pointed out above, the vapour will begin to condense. A tiny droplet will form on each ion, but since many ions are produced in the wake of an alpha particle these droplets will coalesce creat-

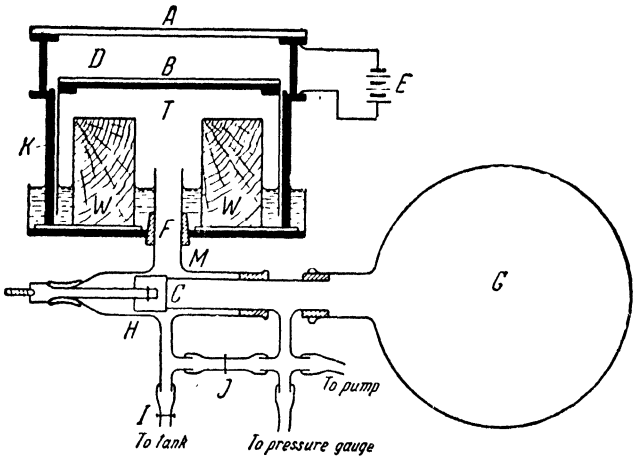


Fig. 5. Diagram of a Wilson cloud chamber.

ing a solid line in the form of a streak, or, as it is commonly called, a track of the alpha particle.

In 1912 Wilson built an instrument embodying this principle. Physicists call it a Wilson cloud chamber, or simply a cloud chamber.

Fig. 5 shows a diagram of such a chamber. It is a short metal tube *K*, in which a piston *B* can move. This forms a bottom to the chamber. The upper end of the tube is covered with a glass disc *A*, through which condensation of vapour inside the chamber *D* (which is filled with saturated water vapour or a mixture of the vapour of water and alcohol) is observed. If the air under the piston is evacuated, the piston will fall, thus increasing the volume of

the chamber *D*. The distance which the piston can fall is regulated and is fixed by special side pieces in the tube where the piston moves. Tube *F* connects the space under the piston with a vessel *G* in which a vacuum and high pressure is alternately created by pumps. Valve *C* separates the space *G* from *T*.

Before the work cycle begins a high pressure is created in vessel *G*. The volume *G* is connected with *T* making piston *B* rise to its upper position. Then with the aid of valve *C* the space *G* is separated from space *T*, rarefying the air in vessel *G*. The valve *C* is then again opened making the pressure under the piston fall suddenly; the piston falls and condensation of vapour begins in the volume of chamber *D*. An electric field, produced by a storage battery *E*, is created between the cover and the piston in order to remove extraneous ions, which under normal conditions are always found in the chamber in small quantities, and also the ions which remain in it after an observation, and which can hamper subsequent observation. At the instant of observation the field is thrown off. In order to observe better the tracks that form in the chamber, the upper part of piston *B* is covered with a layer of blackened gelatin. The wooden cylinders *W* are placed in the space under the piston to reduce the amount of air passing through tube *F*; this makes for a more sudden falling of the piston.

The cloud chamber underwent subsequent improvement, but its principal features have been retained. The observation of the tracks of alpha particles in a cloud chamber creates an unforgettable impression. The alpha tracks rise up before the eyes as "living" things.

Physicists very soon learned to photograph these tracks, and such pictures began to serve as objective evidence giving a vivid description of the behaviour of alpha particles and recording all the vicissitudes of their movement. Such photographs are shown in Figs. Ia, Ib and II (see Appendix). On them we see tracks left in a cloud chamber by alpha and beta particles. Fig. II shows the tracks of numerous alpha particles emanating from a radioactive preparation. All alpha particles have one and the same range in the gas of the cloud chamber.

The Photographic Method of Registering Alpha Particles

This method was proposed in 1910. In studying the photographic effect of alpha particles it was noted that each alpha particle produces a blackening (detected upon development) of the grain of the light-sensitive layer through which it has passed. This blackening of individual grains is easily seen under a microscope.

If a weak radioactive preparation is brought into contact with a photographic plate, the alpha particles emerging from it will impinge on the plate causing the light-sensitive layer to blacken. Some of the alpha particles will shoot almost along the surface. In their movement in the light-sensitive layer, they will pass through numerous individual grains. After the plate has been developed it will exhibit clearly the tracks of these alpha particles. Fig. III in the Appendix shows one of such microphotographs. The place where the radium-coated point was is clearly visible. Also nicely visible are the radial rays that correspond to the trajectories of alpha particles.

For a long time, the photographic method was not in very much use in nuclear physics. Only recently, due in part to the work of the Soviet scientists L. Mysovsky and especially A. Zhdanov, who developed special photographic plates with thick light-sensitive layers, has the photographic method begun to be used in nuclear investigations. At present it is one of the basic methods of nuclear physics.

The path traversed by a particle in the emulsion of a photographic plate is not long, roughly a thousand times shorter than that in air. Whereas the range of an alpha particle in air is several centimetres, in the emulsion of a photographic plate it comes to several tens of microns (1 micron $= 10^{-4}$ cm.). For this reason, the tracks of particles in an emulsion have to be viewed under a microscope.

One plate can contain the tracks of many tens and hundreds of thousands of particles. Thus, one photographic plate can take the place of a huge number of cloud-chamber pictures. However, the merit of the photographic method is not only that one plate contains many tracks, though this is of great importance in certain cases. The microphotographs

of tracks left by particles in the emulsion of a photographic plate enable us to obtain much data concerning the particle under investigation. Thus, in a number of cases, the entire track of a particle may be observed in the emulsion, and, as we know, the length of the track of a particle determines its energy. Besides the total range, it is also possible to determine the ionizing capacity of the particle. This is best done in special small-grained plates. From the number of blackened grains of the emulsion (counted on a definite section of the range) it is possible to establish the ionizing power of the particle, a value that characterizes the number of ion pairs produced by the particle per unit length of its path. Knowing this value, it is possible to determine the velocity of the particle. As we shall see further on, the velocity of the particle and its range will give its mass too.

Figs. IV to IX at the end of the book show several microphotographs with tracks left in the emulsion of photographic plates by different particles. These photographs will be discussed at length in a later section.

To summarize, by 1910-1912 scientists had at their disposal a rather rich assortment of different methods for studying radioactive rays. And before long the work of these scientists opened up before us an unusual panorama of the intra-atomic world. A little later on we shall deal with this picture in more detail, but for the present let us return to the problem we have been discussing, that of the formation of helium from radium and radon.

The Charge of an Alpha Particle

To determine the charge of an individual alpha particle one had to know how many alpha particles shoot out from one gram of radium per second. By taking a definite quantity of radium immediately after it had been purified chemically, and by measuring with a Geiger counter the number of alpha particles, Rutherford and Geiger counted the number of alpha particles ejected in one second by one gram of radium. According to their measurements it came to 3.7×10^{10} (thirty-seven thousand million!) alpha particles.

If we know how many alpha particles radium emits, it is possible to determine the charge of a single particle. To do this, one has only to measure the total charge of all alpha particles emitted by one gram of radium or any other definite quantity of it and then divide this charge by the already known number of alpha particles.

Experiments showed the charge carried in one second by the alpha particles emitted from one gram of radium to be 33.2 absolute electrostatic units. By dividing this number by 3.7×10^{10}, we find that the charge of one alpha particle is equivalent to 9×10^{-10} absolute electrostatic unit, which is twice the charge of a single electron.

Rutherford's hypothesis received one more confirmation. It was found that an alpha particle carries a double elementary charge. Later, a more precise value was obtained for this charge. It came out 9.58×10^{-10} absolute electrostatic unit, which is very close to the double value of the charge of an electron ($4.78\times10^{-10}\times2=9.56\times10^{-10}$).

The Decay Time of Radium and Uranium

We have thus far determined the charge of a single alpha particle, we have also measured the number of alpha particles emitted by one gram of radium in one second. This latter fact enables us to draw a number of new and extremely important conclusions. But first let us take note of one remarkable fact.

We have already pointed out that the activity of certain radioactive substances, for example, radium emanation, attenuates rather quickly. One way of judging this loss of activity is by the reduction in the number of alpha particles emitted by radium emanation in unit time.

The quite natural desire was to find the quantitative law that expresses this loss of radioactivity. Variations in the number of alpha particles emitted by the emanation was a point of careful observation. It appeared (Fig. 6) that the number of alpha particles emitted by a given quantity of emanation diminishes in time according to the following relation:

$$N=N_0e^{-\lambda t}. \qquad (4)$$

Here N_0 signifies the number of alpha particles emitted by emanation in unit time at the very beginning of observations, and N, the number of alpha particles emitted in unit time at the expiration of t seconds; e is the base of natural logarithms, and λ a value that shows what portion of atoms decays in one second.

The most remarkable thing was that in all cases when dealing with emanation, the coefficient λ was one and the same: 2.1×10^{-6} sec.$^{-1}$. No matter what the quantity taken

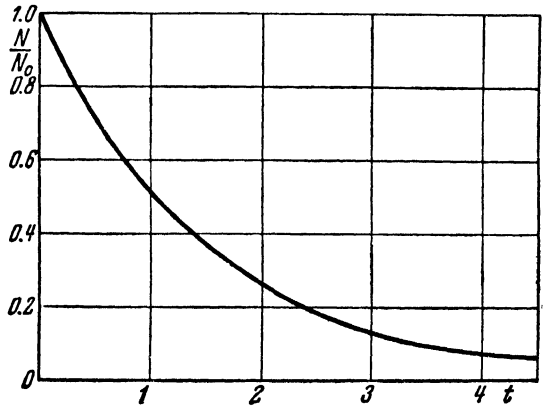


Fig. 6. Radioactive decay curve (the ratio of the quantity of radioactive substance N and the initial quantity of substance N_0 as a function of time t).

was, big or small, λ did not change. For this reason, it was agreed to call λ the decay constant.

What we find in the way of the variation of intensity of radiation as a function of time will appear especially remarkable when we recall the properties of an exponential relation [$e^{-\lambda t}$ in equation (4)]. Equation (4) shows that in one and the same period of time, the intensity diminishes the same number of times. No matter what quantity of radioactive substance is taken, a definite part of it $\left(\frac{N}{N_0}\right)$, equivalent to $e^{-\lambda t}$, disintegrates in one and the same time t. Whether we make our measurements at the beginning of the decay (with a freshly prepared sample of the substance) or

after a certain period of time, when a considerable part of the radioactive substance has already disintegrated, we shall find that the intensity of radiation in both cases will have changed the same number of times during equal periods of time. This means that as the radioactivity of the substance falls off the quantity of atoms decaying in unit time decreases, but the probability of decay remains constant.

The less the quantity of substance the slower it disappears as a result of decay. Strictly speaking, according to equation (4) decay ceases (that is, N becomes zero) only when t equals infinity. If such is the case, how can we then speak of the "decay period" of uranium, radium and other radioactive substances?

Let us agree to characterize the decay time of radioactive substances by the time during which one half of a given quantity of substance decays. This period will always be the same irrespective of the quantity of substance, and, consequently, it is a very definite characteristic of the rate of radioactive decay. *The time in which one half of a radioactive substance decays is called its "half-life."*

To find λ it is convenient to reproduce the curve shown in Fig. 6 in semilogarithmic coordinates, i. e., to plot on the ordinate not the ratio $\frac{N}{N_0}$ but the logarithm of this ratio, and the time t on the abscissa, as before.

In these coordinates, the decay curve, as may be seen from Fig. 7, is a straight line, the tangent of the angle of inclination α of which to the abscissa is what gives the value λ.

If we know the value of λ, then applying equation (4) it is very easy to find the time T during which the intensity of radiation of any quantity of the given radioactive substance is reduced two-fold. To do this, put $N=\frac{N_0}{2}$ in equation (4) and in place of t write T as the exponent. After cancelling N_0 we obtain

$$e^{\lambda T}=2.$$

Taking logs of both sides of this expression, we have

$$T=\frac{\ln 2}{\lambda}=\frac{0.695}{\lambda}.$$

From this relation we shall find for radium emanation (the λ of which, as we have already pointed out, is equal to 2.1×10^{-6} sec.$^{-1}$) that T is 3.82 days.

For all samples of radium emanation this value (just as the decay constant λ, of course) proved to be one and the same. Subsequent observations showed that this law of decrease in radioactivity is observed not only in the case of radium emanation; it is far more general in char-

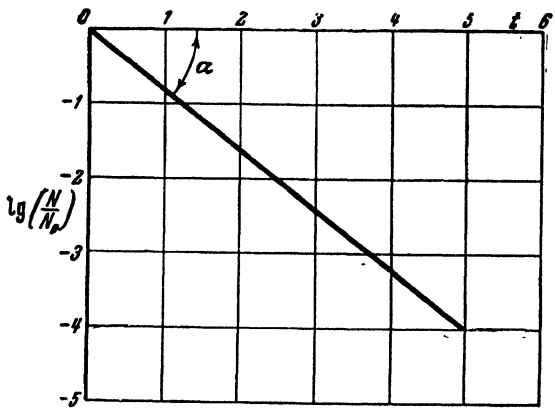


Fig. 7. Radioactive decay curve in semilogarithmic coordinates. The tangent of angle α is equal to the decay constant.

acter. All radioactive substances decay in accordance with the same law, but the values of the decay constant λ of different radioactive substances differ.

More, it was found that if the change in the number of particles emitted by a radioactive substance is expressed by a more complex law than equation (4), then we were dealing with a *mixture* of different radioactive substances. After their separation, it was always found that in each of them individually the number of emitted particles varies exponentially (4) with time.

From the fact that there exists an attenuation of intensity of radioactive radiation and that the intensity varies according to the exponential law, it follows that:

1) the number of emitted alpha particles is proportional to the quantity of the radioactive substance;

2) a reduction in the number of alpha particles is due to a reduction in the quantity of radioactive substance (a radioactive substance, emitting alpha particles, changes its properties and becomes another substance);

3) not all atoms of a radioactive substance emit alpha particles simultaneously. Only a part of the radioactive substance emits alpha particles (or other particles, comprising radioactive rays) at a given time. The greater the half-life, the smaller the quantity of substance that decays, say, during one second.

Let us now determine the half-life of radium and uranium. According to measurements by Rutherford and Geiger, one gram of radium emits in one second 3.7×10^{10} alpha particles, but in one gram of radium there are 2.7×10^{21} atoms. Therefore, the disintegration constant of radium λ_{Ra} is:

$$\lambda_{Ra}=\frac{3.7\times10^{10}}{2.7\times10^{21}}=1.37\times10^{-11}\ \text{sec.}^{-1},$$

and the half-life of radium is:

$$T_{Ra}=\frac{0.695}{\lambda_{Ra}}=5\times10^{10}\ \text{sec.}=1{,}600\ \text{years.}$$

Thus, the half-life of radium is 1,600 years. Only in 1,600 years will its radiation intensity be reduced by one half.

When these data were obtained it became clear why it had seemed before that radioactive substances emitted rays with constant intensity. In actuality, radium was found not to be eternal. It disappears by emitting radioactive rays and is transformed into helium and radon.

The figures for uranium were still more startling. The quantity of alpha particles emitted by one gram of uranium was determined by the same method as in the case of radium. It was found that one gram of uranium emits in one second 1.25×10^{4} alpha particles. If we repeat for uranium the calculation done for radium, we find that

$$\lambda_{U}=5\times10^{-18}\ \text{sec.}^{-1},$$

$$T_{U}=\frac{0.695}{\lambda_{U}}=1.45\times10^{17}\ \text{sec.}=4.4\times10^{9}\ \text{years},$$

where λ_U denotes the decay constant of uranium and T_U its half-life. Uranium decays so slowly (one half every four and a half thousand million years) that it is not surprising that after scientists learned about this phenomenon, they considered the radioactivity of uranium to be eternal. Actually, however, the quantity of uranium and radium diminishes all the time due to decay, and there is an accompanying attenuation of its radioactivity.

The half-life of radium is 1,600 years. If the supply of radium were not being replenished, then in 16,000 years there would only be one-thousandth left, and in 32,000 years, only one-millionth of the original quantity. In several hundred thousand years there wouldn't be a trace of radium left.

Such would be the case, if there were no uranium in the earth and if uranium, in decaying, did not replenish the radium supplies. It is for this reason that we find radium only in combination with uranium. And that is not all, there must exist a definite ratio between the quantities of uranium and radium in the ore. Suppose we took a piece of pure uranium, in which there was no radium to begin with. Radium would begin to appear in the process of the decay of uranium. Its quantity would increase as the uranium decayed if radium itself did not, in its turn, decay.

The number of decaying atoms of radium depends on their number. As the quantity of radium increases, there will be an increase in the number of disintegrating atoms. The decay of radium will diminish the accumulation of its atoms. The growth of the radium impurity will begin to slow down, and the more radium there is, the more its subsequent accumulation will be retarded. And, finally, there will be so much accumulated radium in the uranium that the quantity of disintegrating atoms of radium will equal the number of radium atoms produced by the uranium. There will set in a state of equilibrium, and although uranium decay will continue, still the total quantity of radium will not increase, though new radium atoms will continue to be produced because, as we have already pointed out, the number of old atoms of radium decaying equals the number being produced.

It is easy to find the ratio between the quantity of radium and uranium in the equilibrium state.

Indeed, if the amount of uranium in the ore is N_U grams, then a total of $\lambda_U \times N_U$ grams of radium should be formed in one second, where λ_U is the decay constant of uranium. On the other hand, if the ore contains N_{Ra} grams of radium then the number of grams of radium that should disappear in one second is $\lambda_{Ra} \times N_{Ra}$. Here λ_{Ra} is the decay constant of radium. Both of these quantities are equal when in a state of radioactive equilibrium. Hence,

$$\lambda_{Ra} \times N_{Ra} = \lambda_U \times N_U$$

$$\text{or } \frac{N_{Ra}}{N_U} = \frac{\lambda_U}{\lambda_{Ra}} = \frac{T_{Ra}}{T_U} = \frac{1{,}600}{4.4 \times 10^9} = 3.6 \times 10^{-7}.$$

Thus, we come to the conclusion that there must exist in the ore a definite and invariable ratio between the quantity of radium and uranium. This ratio should equal the ratio of their half-lives, namely, every three tons of uranium in an ore (which has reached the state of radioactive equilibrium) should contain one gram of radium. This will be true, of course, if the uranium ore has existed long enough for the equilibrium between radium and uranium to set in.

The deduction of the ratio $\frac{N_{Ra}}{N_U} = 3.6 \times 10^{-7}$ arrived at on the basis of conclusions relating to the lifetimes of uranium and radium was verified by experiment. An investigation was made of the chemical composition of a large number of uranium ores extracted at different points of the globe and it was found that, with very few exceptions, the percentage of radium contained in the uranium was always the same—an average of one gram of radium per 3.2 tons of pure uranium. Agreement with the theoretical result (one gram of radium in three tons of uranium) was excellent.

The slight discrepancy between these two figures is apparently the result of measurement errors. Therefore, we have every ground for drawing the conclusion that experiment has once again confirmed the conclusions of the theory of radioactive decay.

Once More About the Energy Contained in Atoms of Radium

We have already pointed out that radium is constantly giving up energy. Measurements made by Curie show that one gram of radium liberates 140 calories in one hour. But during this time only a very small part of it disintegrates (no more than 5×10^{-8} gram). Therefore, when the whole gram of radium decays there is released an enormous quantity of energy equivalent to 280×10^4 large calories.

To show how big this figure is, let us compare it with the energy produced in ordinary chemical reactions.

The most energetic reaction occurs in the combustion of hydrogen. When one gram of hydrogen burns (that is, when it unites with eight grams of oxygen) it releases 34 large calories, which is roughly 100,000 times less than that produced by one gram of radium. This comparison is sufficient to show how great is the energy stored up in radium atoms. Further on we shall see that the supply of energy in atomic nuclei is considerably greater than the foregoing data suggests.

Radioactive Series

When certain radioactive substances disintegrate they give rise to new substances which also possess radioactive properties. Thus we know that uranium produces radium, and radium in turn produces radon (emanation) which is also radioactive. What are the decay products of radon? Are they radioactive? Is radium obtained directly from uranium or is it a product of many radioactive transformations?

Scientists were naturally interested to know the full history of all radioactive transformations and the interrelation of all substances thereby produced. The chain of related transformations proved to be a very long one and it was no easy task to get to the end. Many of the peculiarities of radioactive disintegration had to be invoked before, finally, the whole picture appeared clear and the nature of all transformations was discovered and proved conclusively.

In this work wide use was made of several facts: first, of the fact that the products of radioactive decay differ

chemically from the parent substances; second, the half-life of each radioactive substance is a constant value characteristic of the given substance, and third, the energy of the particles emitted in a decay process was found to be a value that characterized the given disintegration.

From these peculiarities of radioactive disintegration scientists were able to establish a genetic relationship between all the decay products. Taken together, the decay products of a given element became known as a radioactive series. For a long time, three such series were known: uranium-radium, thorium and actinium. Tables I to III carry the schemes of mutual transformations in these series. In recent years, the existence of a fourth series, that of neptunium, which will be given in Chapter XI, has been established.

In the schemes of radioactive transformations in the series of uranium, thorium and actinium, the symbol of each product produced in a transformation is enclosed in a circle which also contains two important numbers that characterize the transformed substance. The upper number is the mass number; it indicates the mass of the atom and represents the closest integer to the value of the atomic weight of the given substance. The lower number is the atomic number (the number of the element in the periodic system, and the one that determines its chemical properties). The arrow between the parent substance and the daughter substance indicates the direction of radioactive transformation. The Greek letters α and β placed above or at the side of the arrows indicate: α—that alpha rays (the nuclei of helium atoms) are emitted in the transformation process, β—that beta rays (electrons) are emitted in the process. The numbers under the arrow denote the half-life in seconds, minutes, hours, days and years.

A consideration of the transformations given in the schemes of the uranium, thorium and actinium series reveals a number of very remarkable consequences, the first of which became known as the "displacement law." The displacement law characterizes the change of chemical properties of the substance resulting from radioactive decay. By correlating the atomic numbers of the parent and daughter substances it is easy to see that in the case of alpha decay, that is, de-

cay with the emission of alpha rays, the atomic number of the substance is reduced by two units. However, if we have beta transformation, that is, if in the decay process electrons are emitted, the atomic number of the daughter substance increases one unit. Thus, for example, radon arises through the emission of alpha particles from radium. The atomic number of radium is 88, that of radon 86. RaC is formed from RaB (Table I) by the emission of beta particles. The atomic number of RaB is 82, that of RaC, 83, or one unit more. It is precisely this change in the atomic number, which occurs in radioactive decay, that is the essence of the displacement law discovered by Fajans and Soddy and stated as follows: *when alpha rays are emitted during the disintegration of a radioactive element, the resulting daughter product will be an element with chemical properties and atomic number in the Periodic Table two places to the left of the parent; when the radioactive substance decays with the emission of beta rays (electrons), the daughter substance produced will chemically be an element in the Periodic Table one place to the right of the parent.*

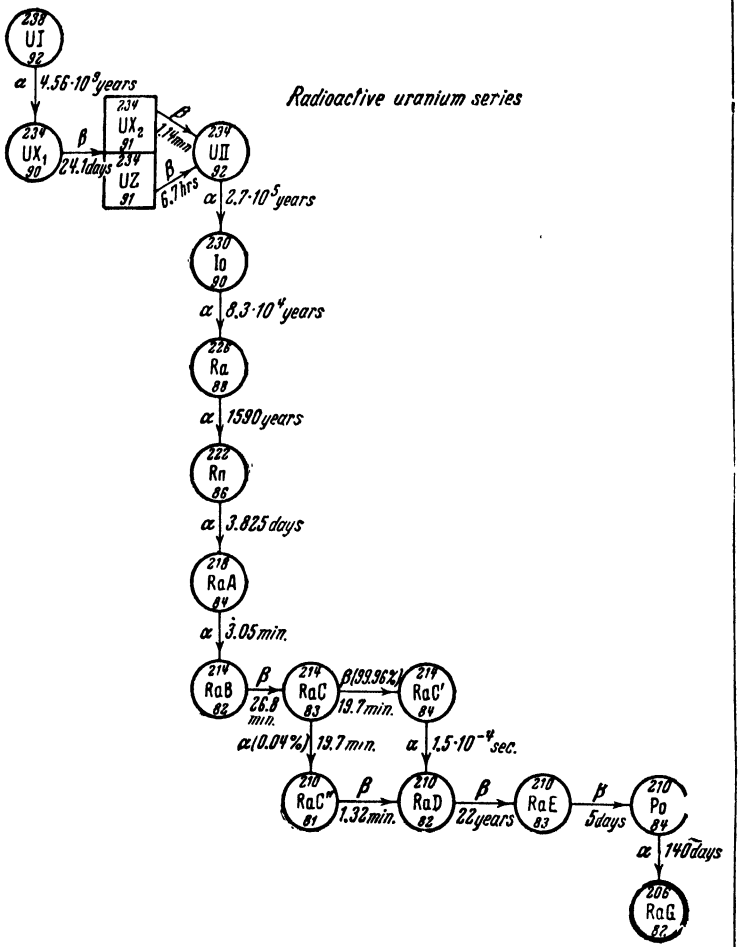
It is obvious that the atomic weight of an element produced by alpha disintegration will be four units less than the original one. The atomic weight of the element produced by beta decay will be the same as in the case of the original element.

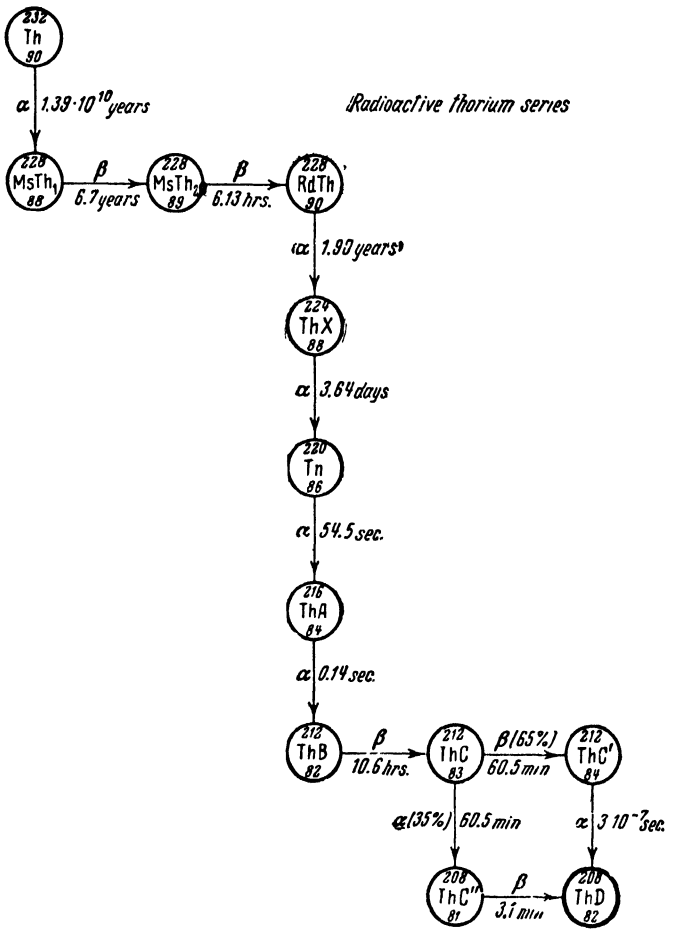
The displacement law plays a very big role in substantiating the modern theory of atomic nuclei. Further on we shall again return to it. Now let us consider other consequences that follow from the established scheme of radioactive transformations in the uranium, thorium and actinium series.

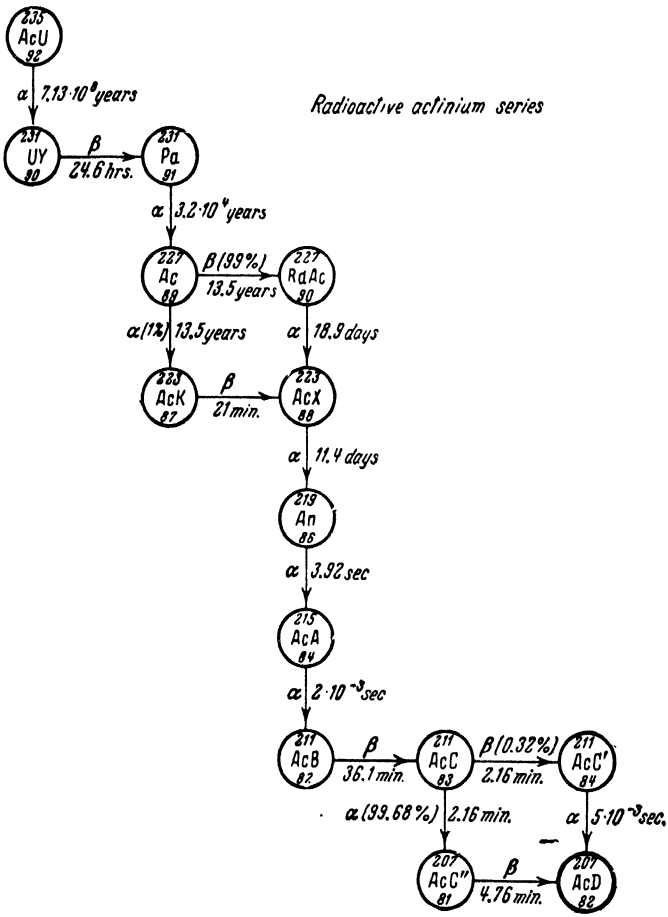
Isotopes

A consideration of the schemes of transformation of all he three series reveals the existence of many different radioactive substances that are identical in their chemical properties. The identity of chemical properties in our scheme is expressed by the fact that all these substances have one and the same atomic number. Thus, for example, in our schemes six different substances: uranium X_1, (UX_1)

Table 1


Radioactive uranium series
238 UI 92
α 4.56·10⁹ years
234 UX1 90
β 24.1 days
234 UX2 91
β 1.14 min
234 UII 92
234 UZ 91
β 6.7 hrs
α 2.7·10⁵ years
230 Io 90
α 8.3·10⁴ years
226 Ra 88
α 1590 years
222 Rn 86
α 3.825 days
218 RaA 84
α 3.05 min.
214 RaB 82
β 26.8 min.
214 RaC 83
β(99.96%)
214 RaC' 84
19.7 min.
α(0.04%) 19.7 min.
α 1.5·10⁻⁴ sec.
210 RaC'' 81
β 1.32 min.
210 RaD 82
β 22 years
210 RaE 83
β 5 days
210 Po 84
α 140 days
206 RaG 82


232 Th 90
α 1.39·10^10 years
Radioactive thorium series
228 MsTh1 88
β 6.7 years
228 MsTh2 89
β 6.13 hrs.
228 RdTh 90
α 1.90 years
224 ThX 88
α 3.64 days
220 Tn 86
α 54.5 sec.
216 ThA 84
α 0.14 sec.
212 ThB 82
β 10.6 hrs.
212 ThC 83
β(65%) 60.5 min
212 ThC' 84
α(35%) 60.5 min
α 3·10^-7 sec.
208 ThC'' 81
β 3.1 min
208 ThD 82



Radioactive actinium series

and ionium (I_0), thorium (Th) and radiothorium (RdTh), uranium Y (UY) and radioactinium (RdAc) have the atomic number 90.

Radioactively speaking, all these substances exhibit radically different properties. UX_1 emits beta rays, ionium emits alpha rays, radiothorium and radioactinium also emit alpha rays, but their decay periods differ. Ionium has a half-life of 83,000 years; radiothorium decays by one half in 1.9 years, and radioactinium in 18.9 days. The mass of the atoms of the radioactive substances produced is also different. The mass number of ionium is 230 atomic units, the mass number of UY is 231, that of radiothorium 228, of thorium 232, of radioactinium 227, and of UX_1 234 atomic units. All these substances, as we see, are different, despite the fact that their chemical properties are absolutely identical. This astounding identity of chemical properties in the case of utterly different atoms was first discovered as early as 1906 in ionium and thorium. By mixing homogeneous compounds of thorium and ionium, scientists found that they were unable in any way to separate them again. In all chemical transformations ionium and thorium behave in exactly the same way.

Thus, radioactive transformations show that at least among radioactive substances there exist different species of the same chemical elements. These species differ in their radioactive properties and therefore are distinguishable. An especially remarkable fact was that different species of chemical elements have different atomic weights (the mass of the atoms measured in atomic units is numerically equal to the atomic weight). It may be recalled at this point that precisely the atomic weight had been up till then considered the basic principle for systematizing the chemical elements; it was immediately found that substances that differ sharply in atomic weight have identical chemical properties. For example, UX_1 has an atomic weight of 234, while radioactinium has 227. But chemically they are absolutely the same. And this is not the only case. Radium B(RaB) has an atomic weight of 214, while its chemical twin, thorium D(ThD) has 208. We shall see later that it is not the atomic weight which determines the conduct of chemical elements.

To summarize, radioactive transformations show that there may be several different representatives of the same chemical elements. And also that this apparently is a property not only of radioactive substances but of stable elements as well. For instance, we find Radium G as the end product of the transformations of the uranium series. Its atomic weight is 206. Thorium D is the end product of the thorium series with an atomic weight of 208. And both thorium D and radium G are chemically identical with lead. For this reason, radium G is called radium lead, and thorium D, thorium lead. Thus the stable element lead has several representatives too. Soddy, the first to detect species of chemical elements among radioactive products, suggested the name isotope for these different representatives of one and the same chemical element. The name isotope (the Greek *isos* meaning equal and *topos* meaning place) is used to designate elements that have the same place in the Periodic Table. Isotopes are species of one and the same element that have different atomic weights. This latter fact (difference in atomic weight) is stressed to distinguish it from the possible case when different representatives of one and the same element that are radioactively different still have the same atomic weight. Such a case is found among the products of radioactive transformations. Thus, uranium Z and uranium X_2, both of which come from uranium X_1 (see Table I) have the same atomic number (i. e., they are chemically identical) and the same atomic weight, 234. Both are formed from uranium X_1, by beta transformation. Despite the same atomic number and the same atomic weight, they differ in radioactive properties. Uranium Z emits beta rays, i. e., electrons, and has a half-life of 6.7 hours. Uranium X_2 also emits electrons, but its half-life is only 1.14 minutes. Uranium X_2 decays 350 times faster than uranium Z. Both substances are thus different, though their atomic numbers and atomic weights are the same. Such substances are called isomers. (To distinguish the isomers of uranium X_2 and uranium Z from the other radioactive substances, their symbols in Table I are placed in squares instead of circles). Isomers are relatively rare, whereas isotopes are extremely prevalent. For example, in the uranium, thorium, and actinium series we have found six representatives of element 90, three of

element 91, seven of element 82, again seven of element 84, and four of element 83.

We shall see presently that the nonradioactive chemical elements also have a goodly number of isotopes.

Brief Summary

Let us bring together what we have discussed in this chapter. The displacement law, which finally established the chain of connected transformations of radioactive elements, was stated in 1913, that is, nearly twenty years after the discovery of radioactivity. The once mysterious phenomenon had lost its veil of mystery. Much was still obscure but the essence of the phenomenon of radioactivity was already understood. Radioactive rays point to the transformation of one sort of atoms into those of another sort. Radioactive rays are a signal of the transformation of chemical elements. It does not take place throughout the entire substance at once. Only individual atoms undergo this change at a given instant. The other atoms disintegrate later.

The probability of disintegration is a constant. In some substances it is small: they decay slowly (uranium, thorium). Thousands of millions of years pass before they decay by one half. This process is fast in other radioactive substances. The probability of decay of the atoms of such substances is great. Some of them (ThC′ for example) have half-lives of millionths of a second.

Radioactive transformations are of two types. In one, electrons are emitted, and in the other, alpha particles. It has been proved that alpha particles are doubly ionized atoms of helium. The identity of alpha particles and helium atoms has been confirmed both by measuring the relation e/m (charge to mass) and by direct observation of the spectrum of a gas formed of alpha particles that penetrate an evacuated tube. The nature of the transformation has in certain cases been checked by a number of control experiments. The transformation of radium into radon was the subject of especially careful study. It was proved by weighing that the sum of the masses of an alpha particle and an atom of radon is equal to the mass of an atom of radium.

A number of ingenious and refined methods of observing and counting individual alpha particles and electrons were developed during the study of radioactivity. These methods made it possible to count the charges of individual particles and to draw a number of very important conclusions, some of which will be discussed in the following chapters.

The discovery of radioactivity, the complex structure of atoms and the transformation of elements was of great significance in the struggle of the materialistic world outlook with idealism. The fall of the metaphysical views of the immutability and indivisibility of atoms that followed the discovery of radioactivity, and the creation of new conceptions about the nature of electrons and atoms that reflect more fully the properties of these particles were utilized by reactionary philosophers to reinstate the idealistic viewpoint. They contended that the process of our cognition was subjective in character. V. I. Lenin was the one who dealt a devastating blow at these attempts to use the latest achievements of physics against materialism. His remarkable book *Materialism and Empirio-Criticism* appeared in 1909, during the period of rampant reaction in Russia. In this book, Lenin tore to shreds the web of mysticism, idealism and empirio-criticism and in its place put the theory of knowledge of dialectical materialism. He showed that "the latest discoveries of natural science — radium, electrons, the transformation of elements — have remarkably confirmed Marx's dialectical materialism..."* because, as Lenin wrote, "the destructibility of the atom, its inexhaustibility, the mutability of all forms of matter and of its motion, have always been the stronghold of dialectical materialism."**

The further development of our knowledge of atomic nuclei which will be described in the chapters that follow is the most vivid illustration of Lenin's profound reasoning when he said that "the electron is as inexhaustible as the atom, nature is infinite, but it infinitely *exists*..."***

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* V. I. Lenin, *Selected Works*, Vol. I, Part 1, Moscow 1952, p. 77.

** V. I. Lenin, *Materialism and Empirio-Criticism*, Moscow 1952, p. 271.

*** V. I. Lenin, *ibid.*, p. 291.

and confirms the principle of dialectical materialism concerning the mutability of all forms of matter and its motion.

· The hypothesis of radioactive decay disproved the earlier established view of the immutability of the atom. The existence of a large number of radioactive isotopes threw doubt upon the assumption that the periodicity in the chemical properties of elements is determined by the atomic weights. All this played a big role in the development of science concerned with the properties of atoms. But of still greater significance were the phenomena and investigations to be discussed in the next chapter.

Chapter II

THE NUCLEAR MODEL OF THE ATOM

In this chapter we describe the work that established with finality the existence in atoms of so-called nuclei, to a description of the properties of which this whole book is devoted.

Scattering of Alpha Particles

The beginning was an insignificant, at first sight, event. Rutherford noticed that the track on a photographic plate of a beam of alpha particles that has passed through a narrow slit is one thing when there is air between the slit and the plate and quite another when there is no air. It was found that if the air is pumped out of the vessel in which the source of alpha particles, the slit and the photographic plate are, the track left by the alpha rays on the plate gives a correct picture of the slit with sharp edges. If this same experiment is conducted in normal conditions with air in the vessel at normal pressure, the result will be different. The track of the alpha particles on the plate bears but a slight resemblance to the form of the slit through which the particles passed: it is much wider and the edges are smeared.

It was not a difficult task to find the cause of such behaviour on the part of the beam. If the air has been removed from the apparatus, the alpha particles shoot between the slit and the plate without encountering any air molecules. They do not suffer collisions and, therefore, do not change the direction of their motion, and so the track on the photographic plate is clear-cut and gives a correct picture of

the slit. The situation is quite different when there is air between the slit and the photographic plate. The alpha particles then encounter air molecules on their way from the slit to the plate, and their original direction changes. The nature of the collision (head-on or oblique) and the number of such collisions for different alpha particles slightly differ: some alpha particles are deflected at a greater angle, others at a smaller angle. This results in a kind of scattering of the original beam. This very natural explanation was at once proposed by Rutherford, and the phenomenon itself received the name of "scattering" of alpha particles.

The Experiments of Geiger and Marsden

The phenomenon of alpha-particle scattering was discovered in 1906. In later years, many workers studied it. It is easy to see the reason for this interest. If the scattering of alpha particles is a result of their collision with air molecules, then a study of such scattering is a study of the interaction of alpha particles and matter. It might be hoped that this study would supplement the scanty knowledge then available concerning the properties of radioactive rays.

Numerous investigations in this direction were carried out by Geiger and Marsden. They studied the scattering of alpha particles on air molecules and they passed alpha rays through thin sheets of different metals and other substances. They replaced the photographic plate with a more sensitive indicator, a fluorescent screen, on which they could observe the scintillations of individual alpha particles.

Using this far more sensitive method of observing alpha particles, they noticed that whereas the preponderant part of the alpha particles change their direction of motion but slightly, some particles change it very sharply. And what is more, it was found that certain alpha particles change their direction of motion 90°, so that they were observable only if the fluorescent screen was put on the side. In one of the experiments the screen was put in such a way that the alpha particles could impinge on it only if after an en-

counter they began to move backwards, i. e., in a direction opposite to that prior to the encounter. Careful observation revealed scintillations in this case also, though the number was very small.

When studying the scattering of alpha particles at angles greater than 90° it was found that the relative number of alpha particles scattered at such big angles differs with the substance. Thus thin metal foils with a large atomic weight scatter alpha particles at angles that exceed 90° in greater quantities than foils of the same thickness but made of metals with a small atomic weight. An increase in the thickness of the plate brings about an increase in the number of alpha particles scattered at big angles.

The Static Model of the Atom

Let us think for a moment about the results of the experiments on particle scattering. It will be recalled that alpha particles shoot out with a tremendous speed, expressible in tens of thousands of kilometres per second. In order to change the direction of motion of the particle even the tiniest bit in the small time interval during which it is sufficiently close to an atom of matter, a huge acceleration must be imparted to it. And to throw an alpha particle back requires truly herculean force. Where does this force come from?

We already know that an alpha particle carries an electric charge and that an electric field produces a definite effect on it. The question arises, do atoms possess electric fields of strength sufficient to do this?

At that time physicists adhered to the nuclear structure hypothesis of J. J. Thomson, according to which all atoms consisted of electric charges. The negative charges are electrons that (in this model) float, so to speak, in matter which fills the entire volume of the atom and is charged positively. The electrons swimming in this medium can produce oscillations, in which case the atom should emit electromagnetic waves, that is, radiate light.

According to Thomson the atoms themselves are in the shape of balls. The total charge of each atom is zero. This

means that the quantity of positively charged matter is such that its charge is completely compensated for by the charge of the electrons.

Thomson's model of the atom explained certain facts that were known at that time. And what is more, one of its basic principles was confirmed directly by experiment. It was established that metals on being heated give off electrons. The presence of free electrons was also observed in discharges in gases. Both these facts show that electrons are really present in atoms. Else, where could they have come from in the foregoing experiments?

The number of electrons in an atom may decrease or, in certain cases, on the contrary, increase depending upon the action from outside. This explained the origin of positive and negative ions.

However, even the very existence of radioactivity is hard to reconcile with this atom model. We know that alpha particles are a constituent of radioactive radiation. Now where do these concentrated positive charges come from, since according to Thomson the positive charge is sort of smeared over the whole atom.

Experiments on the scattering of alpha particles made still more apparent the deficiences of Thomson's model. They showed that it was necessary to allow for the existence inside the atom of concentrated positive charges, for according to Coulomb's law an electric force acting on a charge is proportional to the magnitude of the charge and inversely proportional to the square of the distance between the charges. In order to obtain, using the Coulomb law, a force sufficient to throw alpha particles backwards, one must assume that the alpha particle approaches the charge acting on it to within a distance of the order of 10^{-12} cm. Such must be the concentration of charge to deflect an alpha particle at a big angle! But an electron cannot be such a concentrated charge. The mass of an electron is small in comparison with the mass of an alpha particle, which is some seven thousand times heavier than an electron. With such a ratio of weights, the collision of an alpha particle with an electron would resemble that of a fast moving automobile (weighing about a ton) with a small stone 5 or 6 cm. in diameter lying on the road. A collision of this type could of course send the

stone flying quite a distance, but the automobile would practically not change its direction. It is clear that collisions of alpha particles and electrons, if they do take place, cannot cause the alpha particles to be deflected at big angles. Such encounters might be used to explain only slight deviations of the particles. And since alpha particles are deflected (though very rarely) at big angles, there must be present within the atom positive electric charges concentrated within a volume of diameter not more than 10^{-12} cm. In this volume there must at the same time be concentrated a considerable part of the mass of the atom. It is only in such conditions that an alpha particle, interacting (colliding) with a charge associated with a mass that exceeds considerably the mass of the alpha particle, can change sharply the direction of its motion and recoil. A collision in this case is like a rubber ball hitting a heavy stone—the ball rebounds backwards with ease.

From this simple reasoning there flow consequences of exceptional importance. Obviously, the mass of the atom is not spread over its entire volume, but is concentrated, together with the charge, in a very small space. Since to electrons we attribute a negative charge, which clearly cannot be used to explain the scattering of alpha particles, it was natural to consider the region in which the mass of the atom is concentrated as having a positive charge.

The Nuclear Model of the Atom

The foregoing considerations are but a slight modification of those of Rutherford that served as a basis for his nuclear model of the atom. According to Rutherford, the atom consists of a nucleus that concentrates nearly the whole mass of the atom and its entire positive charge. Around the nucleus move individual electrons, the number of which makes the total charge of the atom zero. The space occupied by the nucleus is extremely small when compared with that of the atom as a whole.

When an alpha particle passes close to one of the electrons in the atom, a strong interaction occurs between the alpha particle and the electron. In this case, one may

speak of the collision of an alpha particle and an electron. The alpha particle may transfer to the electron an energy big enough to knock the electron out of the atom completely. The result of such a collision is two charges: one, the positively charged residue of the atom minus one electron (a positive ion) and an electron, which in the air, usually gets attached to a neutral atom, making the latter a negative ion. Thus, the collision of alpha particles and electrons results in ionization of molecules and atoms. Recall now that the power to ionize gases was one of the first properties of radioactive rays to be discovered.

When an alpha particle passes in the immediate vicinity of a nucleus,its direction of motion changes perceptibly. This we call the scattering of alpha particles.

Quite naturally, this new model of the atom excited tremendous interest among physicists, for it was not so long before that some workers had begun to doubt the very existence of atoms as something real, and now details of their structure were already being discussed. Rutherford's hypothesis had to be verified, new facts had to be found to confirm it. And many prominent scientists set about this verification and began to study the new atomic model.

The first thing was to check this new idea quantitatively. Rutherford himself laid the groundwork by analyzing mathematically the scattering of alpha particles.

Now to recall the problem: an alpha particle in colliding with a nucleus changes the direction of its motion. How much will this change be after one encounter with a nucleus?

Fig. 8 shows diagrammatically the path of an alpha particle. On encountering a nucleus it changed its direction by an angle ϑ. Obviously the angle of deflection of the alpha particle will be the greater, the stronger the interaction with the nucleus, that is, the closer it comes to the nucleus. Some particles will pass close to the nucleus, others at a greater distance. For this reason, alpha particles moving in a given direction are deflected differently after traversing a certain thickness of matter. Therefore, the problem should be to calculate the number of particles (resulting from all kinds of collision) scattering at small angles and the number scattering at large angles. And Rutherford made the calculations. He computed the part of a uniform

beam of alpha particles that scattered at an angle ϑ in passing through a layer of matter whose thickness we shall designate by s. It should of course be clear from the outset that the scattering result will depend not only on the thickness of the layer, but also on its density, since the denser it is the more atoms there will be and the greater the probability of an alpha particle colliding with a nucleus. It is therefore obvious that the probability of alpha-particle scattering depends both on the thickness of s and on the number of atoms n present in a unit volume of the substance.

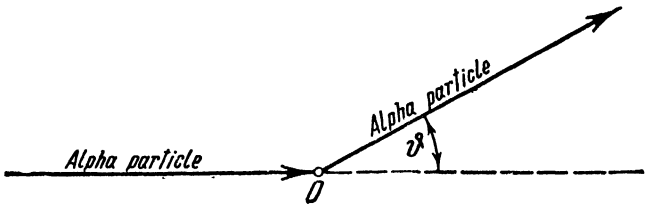


Fig. 8. The scattering of an alpha particle by an atomic nucleus at point *O*.

Further, to calculate the angle of deflection ϑ it was necessary to know the forces acting between the alpha particle and the nucleus. These were believed to be the forces of electrical repulsion which obey Coulomb's law; they should consequently vary inversely with the square of the distance between the particle and the nucleus and should also be proportional to the charge of the nucleus and the charge of the alpha particle. The charge of the alpha particle was already known, being, as the reader may recall, equal to two elementary units. And the charge of the nucleus? In Rutherford's original theory nothing could be said on this score, and in his calculations he simply designated the value of this charge as Z.

From these calculations Rutherford obtained the following equation:

$$N = N_0 \times n \times s \left(\frac{Ze^2}{mu^2}\right)^2 \times \frac{1}{\sin^4 \frac{\vartheta}{2}} \; * \qquad (5)$$

* In this equation the number of particles scattered through the angle ϑ is related to a unit of solid angle.

Here, N denotes the number of alpha particles (of the total number N_0) scattered in traversing a thickness of matter s at an angle ϑ. The other literal symbols are: n, the number of atoms per unit volume of scattering medium (it characterizes the density of the scattering substance); Z, the charge of the nucleus expressed in elementary units (an elementary unit of charge is taken as the charge of an electron and is denoted by e); u is the speed of the alpha particle and m its mass.

It was this equation, which became to be known as the Rutherford equation, that had to be verified. It contains a number of values that had already been determined earlier, for example, e, the charge of an electron, m, the mass of an alpha particle, u, its speed, n, the number of atoms per unit volume of scattering substance. But equation (5) contains a value which had never before been determined — the charge of the nucleus Z.

If we were convinced of the correctness of equation (5), then by measuring the number of alpha particles scattered at an angle ϑ and knowing the number of incident alpha particles, we could calculate from this equation the value of Z. But one had to be sure of the correctness of this equation. How was it to be checked?

Note that in this equation the number of alpha particles scattered at various angles is inversely proportional to the fourth power of the sine of angle $\frac{\vartheta}{2}$ (ϑ is the scattering angle). Obviously, it is necessary to measure the number of alpha particles scattered at various angles and to see whether this number varies in inverse proportion to the fourth power of $\sin\frac{\vartheta}{2}$. If it is found that N varies as $\frac{1}{\sin^4\frac{\vartheta}{2}}$, then there is a grain of truth in Rutherford's equation.

Geiger and Marsden, who had already made a study of the scattering of alpha particles, set about studying the number of alpha particles scattered at different angles. The instrument used in these researches was constructed as follows (Fig. 9). A source of alpha particles S, a metal foil F that scatters alpha particles, and a microscope M used to observe individual scintillations on a screen E were all put

inside a thick-walled cylinder. The source S was screened on all sides by a thick layer of lead at one point of which a narrow slit was cut. Through this slit was passed an almost parallel beam of alpha particles which then fell on a scattering foil F.

The body of the instrument was mounted on a thick disc B equipped with a stopper Q that enabled the whole instrument to turn on the base T even when the air had been pumped out. The source S and the scatterer F were connected with the fixed base of the instrument, and the microscope M and the screen E with the body B. When the whole body was moved, the position of the screen also changed. By observing the scintillations and counting their number for different positions of the screen and microscope, it was possible to determine the number of alpha particles scattered at various angles ϑ.

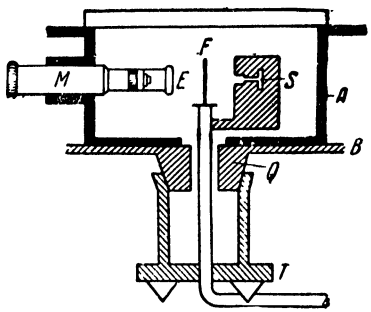


Fig. 9. A Geiger-Marsden apparatus designed to verify the dependence of the number of scattered alpha particles on the scattering angle.

Investigations conducted with this apparatus fully confirmed Rutherford's equation. The number of scintillations grew in proportion to the thickness of the scatterer, and as the angle ϑ increased it decreased in proportion to $\frac{1}{\sin^4 \frac{\vartheta}{2}}$ which was in complete agreement with equation (5).

Confirmation of the correctness of this equation signified acceptance of the nuclear model of the atom. "Atomic nucleus" was from this time on an accepted term.

Having proven the Rutherford equation to be correct, one might then use it to determine Z, the charge of atomic nuclei. Z was measured for several different metals. The charge of the nucleus of an atom of platinum came out to

77 elementary units, that of an atom of silver to 46, and the charge of the nucleus of an atom of copper was 29. Since the accuracy of the measurements reached 1-2 per cent, the error in determining the charges of nuclei could not have exceeded one unit.

The Relation Between the Place of an Element in Mendeleyev's Periodic System and the Charge of Its Nucleus

A determination of the size of the charge of the nucleus of copper, silver and platinum, which was carried out on the basis of an analysis of the scattering of alpha particles, enabled a conclusion of the utmost importance to be drawn. To get a real understanding of the essence of this matter, let us examine the Mendeleyev Table of Elements (see Appendix).

Arrange all the chemical elements in the order given in this table and number them in succession. The number received by each element is called its *atomic number*. The atomic number is the number of the place a given element occupies in the Periodic Table. Thus, for example, hydrogen occupying the first place has an atomic number of one. The atomic number of helium is two because it occupies the second place in the table. Lithium has an atomic number of three (its place is third in the table), beryllium 4, etc. In this table, copper has place number twenty-nine, making its atomic number also 29. But the charge of the nucleus of a copper atom (which charge, as we have already shown, was determined from observations of the scattering of alpha particles), also proved to be 29 elementary units. And so it turns out that the magnitude of the nuclear charge of an atom of copper coincides with the atomic number of copper.

A similar ratio was also found for silver and platinum. Silver has an atomic number of 47, whereas the charge of the atomic nucleus of silver, computed from the results of the scattering of alpha particles, proved to be 46 elementary units, or in other words it coincided with the value of the atomic number of silver within the limits of the accuracy of measurement. The atomic number of platinum is 78,

while the size of the nuclear charge of one of its atoms measured from alpha-particle scattering in platinum came out 77 ± 1.

The coincidence of the atomic numbers of copper, silver and platinum with the size of their nuclear charges could not be fortuitous, and for this reason Van den Brook, who was the first to correlate the results of the measurement of atomic nuclear charges with the position of the elements in the Periodic Table, suggested that *the magnitude of the charge of the atomic nucleus of each chemical element (measured in elementary units of charge) is equal to the atomic number*, that is, the ordinal number which this element has in the Periodic Table.

This conclusion made it possible at last to understand the true nature of the regularity discovered by Mendeleyev. It was now clear what underlay Mendeleyev's Table, in what way the atoms of different chemical elements differ, and what determines their chemical individuality.

An atom in the normal state, as we know, is electrically neutral. Therefore, if the nuclear charge of the atom is Z units, there should be Z electrons in the atom. All atoms are structurally alike. The atom of any chemical element consists of a nucleus and electrons. Atoms differ only in the size of the nuclear charge and, related thereto, the number of extra-nuclear electrons. Thus, for example, the charge of the hydrogen nucleus is unity, and the hydrogen atom has only one electron. Structurally speaking, this is the simplest element. Now it is clear why hydrogen stands first in the Periodic Table.

A helium atom has two electrons because the charge of the nucleus is two units. Let it be noted at this point that an alpha particle is a doubly ionized atom of helium. Therefore, the alpha particle is simply the nucleus of an atom of helium. Its charge is, as it should be, equal to two elementary units.

An atom of the heaviest natural element, uranium, which occupies place number ninety-two in the periodic table consists of 92 electrons and a nucleus with a charge of 92 elementary units.

Now we possess a clear-cut criterion for arranging the chemical elements in order. The confusion which obtained

before when attempts were made to arrange the elements strictly in accord with the order of increasing atomic weights (for example, iodine-tellurium, nickel-cobalt, and potassium-argon) is easily eliminated. Iodine has an atomic weight less than tellurium, whereas in the table its place is after tellurium; potassium is lighter than argon, but in the Periodic Table its place is farther away; nickel has a smaller atomic weight than cobalt, but in the table it is followed by cobalt. Iodine should have a place following tellurium since the nuclear charge of iodine is exactly one unit greater than the nuclear charge of tellurium. In exactly the same way, the nuclear charge of potassium and nickel atoms is greater, respectively, than that of argon and cobalt. The fact that Mendeleyev arranged the elements in his table correctly long before the discovery of the structure of the atom was a truly brilliant prevision.

Soon absolutely reliable evidence was found for the correctness of this hypothesis.

Recall the law of radioactive displacement. According to this law, a substance formed by alpha-radioactive decay is situated in the Periodic Table two squares to the left of the parent substance, while a substance resulting from beta-radioactive decay is located one square to the right of the parent substance. And this is exactly the way it should be on the above hypothesis: if two positive charges are removed from the nucleus, its atomic number becomes less by two units; therefore, we obtain a substance whose chemical properties are given by an element two squares before the initial one in the Periodic Table. On the contrary, if we remove one negative charge (a beta particle) from the nucleus, its positive charge will increase one unit, and this will result in the element moving to the right one square, that is, an increase in the atomic number. What a remarkable and simple explanation of the complex relations of radioactive decay!

Let us turn our attention to one more aspect of the problem. The positive charge exists only in the nucleus, and it is quite natural, therefore, that the alpha particle produced in the process of radioactive decay shoots out of the atomic nucleus. But the number of electrons in the atom is large, and just equal to the number of elementary units

in the charge of the nucleus. However, a removal of these electrons which swarm about the nucleus and for this reason are called extra-nuclear electrons, does in no way create an atomic transmutation. An atom deprived of one of its outer electrons ceases to be neutral, and becomes an ion. No other changes take place. In the course of time, the ion attracts a free electron and again becomes a neutral atom which in no way differs from the original atom.

It is quite another thing to take an electron out of the nucleus. The atomic charge changes. If it was Z, it becomes Z+1. Such an atom will also be a positive ion because the number of extra-nuclear electrons is, as before, Z, and these Z electrons are not able to neutralize the charge of the nucleus which has become Z+1. We must add one more electron to the outer shell. When this occurs, the atom will again become neutral. But its properties will differ from those of the original one, and it will behave like an atom of the next element in the Periodic Table.

To summarize, *radioactive transformations are transformations that have to do with the nuclei of atoms. In radioactive transformation the charge of the atomic nucleus changes.* As a consequence, the number of extra-nuclear electrons changes as do also the atom's chemical properties. The chemical nature of an element is entirely determined by the nuclear charge of its constituent atoms. As long as the nuclear charge remains unchanged, the chemical properties of the atoms will remain constant.

Atoms are not immutable assemblies. By changing the charge of the nucleus it is possible to change the chemical properties of the atoms, that is, to transmute one element into another. However, such transmutation requires tremendous energies. The theory of the immutability of the atom, of the invariability of the chemical elements could arise solely because the processes encountered in earlier times were capable of affecting only the orbital electrons of the atom without producing any changes within the nuclei. But when changes occur in atomic nuclei, not a trace is left of this immutability of the chemical elements. Radioactive phenomena made this quite clear, and physicists finally came to understand the true cause of the transformation of radioactive elements.

Measuring the Charge of the Nucleus with X-Rays

The hypothesis according to which the charge of the nucleus determines the place of the element in the Periodic Table appeared to physicists to be very close to the facts. But it had to be confirmed by direct experiments not only for radioactive elements occupying the end of the periodic system, but also for the remaining stable elements. There was only one way to do this and that was to measure the charges of all nuclei and to make sure that the nuclear charge of the atoms of each element is indeed the same as its atomic number. It was especially important to do this with respect to the unsettled places in the Periodic Table where the regular increase in atomic weight was violated, such as in the afore-mentioned groups: argon-potassium, cobalt-nickel, tellurium-iodine.

This job was accomplished by Moseley, who solved the problem indirectly. In order to grasp the meaning of his investigations we shall have to digress at length.

According to Rutherford the atom of an element consists of two basic parts: the atomic nucleus, the subject of our discussion, and electrons (whose quantity is determined by the size of the nuclear charge) making up the extra-nuclear shells of the atom. This latter part is not directly related to the topic of this book. However, it was found that certain properties of the electronic configuration of the atom might be used to clarify some of the values characterizing the nucleus, and among other things, to determine its charge. That is why we shall discuss in more detail this electronic structure of the atom.

The properties of the orbital electrons were first investigated by Bohr. Using the nuclear model of the atom as a basis, he found the laws that govern the movement of electrons about the nucleus.* According to these studies, the Z electrons in the atom (the nuclear charge of which is

* If the electrons in an atom were at rest the force of electrical attraction to the nucleus would finally draw them to it. Hence, an atom can be in a stable state only if its orbital electrons are in a state of constant motion. They may be likened to the movement of the planets about the sun. Due to this motion, the planets do not fall onto the sun though they are always attracted to it.

also Z) are arranged in different ways. They form different groups, which are distributed in the atom as is diagrammatically shown in Fig. 10, in layers of different radii. These layers (or shells) are designated by the letters K, L, M, N, etc. The shell of electrons closest to the nucleus is denoted by K, the next shell is L, which is followed by M, N, etc., in the order of the alphabet. The number of electrons that make up each of these shells is limited: it cannot exceed

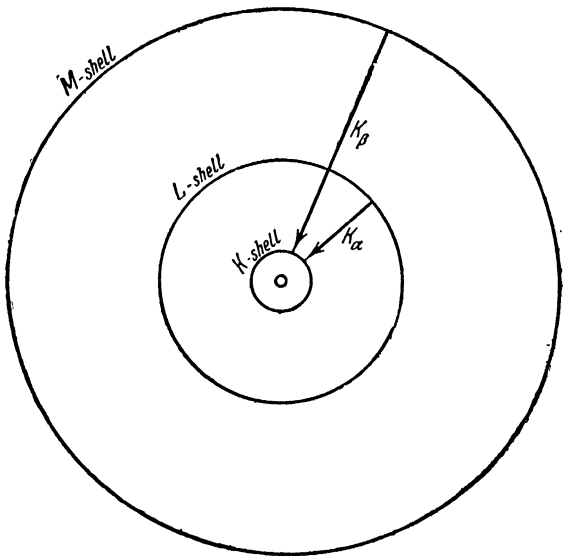


Fig. 10.

a certain very definite limiting value. This value differs with each shell. In the closest K-shell there can be no more than two electrons. The maximum number of electrons which the L-shell can accommodate is eight. The M-shell can hold up to 18 electrons, and the N-shell takes a maximum of 32 electrons. The limit numbers of electrons in the different atomic shells form a very regular series. This regularity may easily be noted. Number the K, L, M, N, etc., shells in order:

$$K,\ L,\ M,\ N,\ O,\ldots$$
$$1,\ 2,\ 3,\ 4,\ 5,\ldots$$

The squares of these ordinal numbers form another series:

$$1,\ 4,\ 9,\ 16,\ 25,\ldots$$

The doubled values of these numbers are respectively equal to

$$2,\ 8,\ 18,\ 32,\ 50,\ldots$$

and coincide with the above limiting figures for the number of electrons that fill the corresponding extra-nuclear electron shells of the atom.

A knowledge of the laws of distribution of electrons in the shells made it possible to find the cause of the periodic repetition of chemical properties in the elements of Mendeleyev's Table. We have already established that in this table the atoms of different chemical elements are arranged in the order of increasing charge of the atomic nucleus, and consequently, in the order of increasing number of extra-nuclear electrons. In the atom of each successive element of the Periodic Table the nucleus has a charge one unit more than the preceding element, and the electronic configuration of the atom of each succeeding element has one additional electron. In what shells are these electrons arranged? To answer this question, let us consider the magnitudes of energy that the electrons in the different shells possess.

As we have already pointed out, the electronic shells are situated at different distances from the nucleus. Obviously, the closer the electrons are to the nucleus, the greater is the attraction of the nucleus that they experience, since the forces of interaction between charges are inversely proportional to the square of the distance between them. For this reason, the electrons in the K-shell are more strongly bound to the nucleus than the electrons of the L-shell. And in turn, the electrons of the L-shell are more strongly bound than those of the M-shell and so forth. Since the electrons in the atom are attracted to the nucleus, a certain amount of work must be done to remove an electron from an atom. The energy required for the ionization of an atom, that is, for the removal of an electron from the atom, is a measure of the binding force of the electron in the atom. Let us denote the energy expended in knocking an electron out of the K-shell by W_K, and the energies required to remove

an electron from the L, M, N,... shells respectively by W_L, W_M, W_N,... Obviously, W_K will be greater than W_L, and the latter will be greater than W_M, and so forth. Since the energy communicated to the electron in its removal from the K-shell is greater than from the L-shell, it is obvious that an electron in the K-shell possesses less energy than in the L-shell. An electron in the K-shell has an energy that is less than that of an electron in the L-shell by a factor of ΔW:

$$\Delta W = W_K - W_L.$$

We are now in a position to answer the question of how the electrons are distributed in the electronic shells of the atom. Since any system strives to pass into a state of lowest possible energy, the electrons entering an atom will strive to occupy places in the K-shell, the L-shell and other free shells of least energy closest to the nucleus. But not all the electrons can get into the K-shell. We already know that this shell cannot accommodate any more than two electrons. The remaining electrons are forced to find places in shells of greater energy. If the nuclear charge does not exceed 10, the number of extra-nuclear electrons in the atom is not over 10, and all the remaining electrons may be arranged in the L-shell which can hold eight electrons. If the number of electrons in the extra-nuclear configuration of the atom is greater than 10 (the nuclear charge exceeds 10), then a part of the electrons have to find places in the M-shell that accommodates 18 electrons, and then in the N-shell, and so on.

The fact that only a limited number of electrons can occupy the inner shells of least energy is what conditions the periodicity in the chemical properties of the elements. As the shells fill up, the electrons arrange themselves periodically in the outer shells. The similarity of the outer electronic shells of atoms determines the likeness of the chemical properties of the elements.

Let us return to the Periodic Table. The first element is hydrogen, the second helium, with an atomic number of two. The nuclear charge of its atoms is also two. Helium has two electrons, both in the K-shell filling it completely. Atoms with their outermost shell filled are especially stable.

Helium is a noble gas and chemically inert. The next element after helium in the Periodic Table is lithium with an atomic number of three. The three extra-nuclear electrons are divided up between the *K*-shell and the *L*-shell with two in the former and one in the latter. This single electron in the *L*-shell has considerably greater energy than the electrons of the *K*-shell. Much less energy is required to dislodge it from the atom. For this reason, an atom of lithium relatively easily gives up its electron from the *L*-shell, entering into compounds with different atoms. The ability of lithium to give up its outer electron is what characterizes its chemical behaviour. Lithium belongs to the group of alkali metals. The elements following lithium, beryllium, boron and carbon have, respectively, two, three and four electrons in the *L*-shell. The number of these electrons determines the chemical valence of the elements. The tenth element, neon, has both the *K*- and *L*-shells filled. A group of eight electrons is especially stable and therefore we find neon as a noble gas. Neon is followed in the Periodic Table by sodium, with an atomic number of eleven. There are eleven extra-nuclear electrons in this atom. Two fill the *K*-shell, eight fill the *L*-shell and the eleventh is in the *M*-shell. Sodium, like lithium, has one weakly bound electron in the outermost shell. This is what explains the similarity of the chemical properties of sodium and lithium. Like sodium, lithium is an alkali metal that easily gives up its weakly bound outer electron.

Bohr's theory not only explained the reason for periodicity in the chemical properties of the elements, but also indicated a new way of determining the nuclear charge of each element. This was done by Moseley. To understand the idea of these measurements, we again refer to the *K*-, *L*-, *M*-, etc., shells, which accommodate the extra-nuclear electrons of the atom. We repeat again that to remove electrons from these shells, energy must be expended equal to W_K, W_L, W_M, etc., respectively. This energy may be imparted to the electrons if the atom is acted on by an outside force, for example, through the impact of an electron or alpha particle. If the acting force is sufficiently great, the electron will be knocked out of the corresponding shell and the atom will thus be ionized. However, the action may not prove so

strong and the electron of the K-shell will receive an energy less than W_K. This is not enough to detach the electron from the atom but it may be sufficient to throw the electron for instance from the K-shell to the L-shell (if it is not filled) or into the M-shell. Such an atom, with an electron transferred from its normal shell to an outer shell, is neutral, it is not an ion. But it differs from the other normal atoms of this chemical element in that it has an excess of energy. Atoms with excess energy are commonly called excited atoms. Thus, an atom may be in any one of three possible states: ground (normal), ionized, and excited. Let us denote the energy of a normal atom by W_0, and the energy of an excited atom by W'.

Now what happens to an excited atom? We already know that an ionized atom, i. e., an atom deprived of an electron tends to revert again to the normal state. To do this, it must catch a free electron from outside. An excited atom does not need to capture anything, since excitation only changes the energy of one of the extra-nuclear electrons, while the number of electrons remains the same. Naturally, such an atom can return to the ground state quicker than an ionized one can. The question arises as to what will become of the excess energy $W'-W_0$ which the atom had in the excited state.

To this query Bohr gave the following answer: *An atom passing from an excited state to ground (normal) state radiates a certain portion of light energy* (equal to the energy of excitation). This portion of light energy is now called a *quantum* of light. What is this light which is radiated?

We know that there are numerous colours of visible light: red, blue, green, etc. We also know of the existence of invisible rays: infrared, ultraviolet and X-rays.

All these different rays have the very same nature; all of them are electromagnetic waves and differ from each other not more than do the sounds of music from each other.

All the distinguishable sounds of music, expressed as notes (do, re, mi, etc.) are also of one and the same nature. They are vibrations of air and differ only by the frequency of the vibration.

In like manner, the different light rays, both visible and invisible, differ only in the frequency of the electro-

magnetic oscillations. The frequency of these oscillations is extremely large. Thus, for example, the frequency of yellow rays emitted by the incandescent vapours of sodium is 5×10^{14} per second. All shades of visible light have frequencies ranging from 4×10^{14} to 8×10^{14} oscillations per second. The frequencies of oscillations greater than 10^{15} per second correspond to invisible (ultraviolet) rays. Invisible also are rays with a frequency less than 4×10^{14} per second (infrared rays). The large range of oscillations from 10^{16} to 3×10^{19} per second is covered by the so-called X-rays. In passing it may be mentioned that the gamma rays, discovered as a component of radioactive radiation are of the same nature as visible light. Gamma rays are also electromagnetic waves, only their frequency is still greater. The frequency of oscillations of gamma rays is of the order of 10^{19} to 10^{21} per second. It is common to designate the frequency of oscillations by the Greek letter ν (nu).

Now to return to our problem. What light will be emitted when an atom passes from the excited state to ground?

On Bohr's theory, it follows that the frequency of the light emitted when an atom passes from an excited state to the ground state depends on the energy difference between the excited and ground states. The greater the energy of excitation, the greater will be the frequency of the light radiated during the transition from the excited state to the ground state.

The exact relation existing between the frequency and the excitation energy $W'-W_0$ is given by Bohr in the following equation:

$$\nu=\frac{W'-W_0}{h}.$$

Here h denotes a constant that plays a tremendous role in atomic physics and is called Planck's constant, which is equal to 6.62×10^{-27} erg-sec. The value $h\nu$, which represents a portion of light energy emitted by one atom, is called a quantum of light.

As far back as the nineteenth century it was known that the radiations of different substances differ. It appears that each chemical element emits rays not of one and the same definite type but in the form of a spectrum, which is

a complex radiation consisting of many different rays. But the spectrum of these rays in the case of each element is specific. This peculiarity of the spectra of different substances is best revealed in the gaseous state.

Further investigations showed that the character of the spectrum which is radiated owing to excitation by the atoms of the given substance, depends on the magnitude of the excitation energy. As the excitation energy increases, new rays appear in the spectrum of radiation. These new rays readily form groups, which are called series. The characteristic feature applied in the grouping of rays into series is very simple. All the individual rays of one series appear in the radiation simultaneously. If the excitation is insufficient, there are absolutely no rays of the respective series; if the excitation energy is greater than a certain limiting value, all the rays of the series appear at once. While studies were confined to atoms relatively feebly excited (for example, heated to several thousands of degrees), the light observed consisted of low-energy light quanta that comprise visible rays, infrared rays, and, in small quantities, ultraviolet rays.

Later, when we learned how to impart to atoms greater excitation, we observed radiation that contained quanta of greater energy. If, as Roentgen noted, atoms are excited by electrons that possess an energy of several tens of thousands of electron-volts, X-rays are produced; these rays are radiation quanta of big energy that are also measured in tens of thousands of electron-volts. Quite understandably, to obtain radiation quanta of such high energy, it is necessary to excite the atom very strongly by endowing it with a big supplementary portion of energy.

This difference in the radiation of atoms with varying excitation energy was fully explained by the Bohr theory. The reason is the difference in the amount of energy that the electrons in different shells have. (According to Bohr's theory, the binding energy of the electron depends on the radius of its orbit, being inversely proportional to the square of the radius of its orbit.) If we knock an electron out of one of the inner shells, the vacant place will be occupied by an electron formerly in one of the outer shells. It is in such transitions that radiation takes place, since

electrons situated in the more distant shells have greater energy. X-rays arise when electrons pass to shells closest to the nucleus.

X-radiation was the subject that Moseley attacked. His attention was especially drawn to the *K*-series which is produced as a result of electron transitions from different shells into the *K*-shell, and, in particular, a line called *K*-alpha (the usual designation is K_α). This line is radiated during the transition of an electron from the *L*-group to the *K*-group (see Fig. 10) and is the most intense line in the *K*-series.

Moseley's interest in the *K*-series and, in particular, the K_α-line, is quite understandable. When the *K*-series is excited, electrons have to be knocked out that are closest to the nucleus, and, consequently, experience the greatest attraction. Besides, *K*-electrons are attracted to the nucleus without their force being reduced by the action of other electrons. It is therefore natural that the influence of the nuclear charge will be most pronounced on the motion of such electrons. Bohr examined this problem theoretically and showed that the frequency of radiation of the K_α-line depends on the size of the charge of the atomic nucleus as follows:

$$\nu = R(Z-1)^2 \qquad (6)$$

where Z denotes, as usual, the size of the nuclear charge in elementary units, and R is a certain constant frequently encountered in radiation theory and equal to 3.29×10^{-15} sec.^{-1}.

Equation (6) shows that the frequency of the K_α-line belonging to the *K*-series of X-rays is related to the size of the nuclear charge under study. It might be expected that a measurement of the frequency of K_α would help us to determine the magnitude of the charge of atomic nuclei. And so Moseley decided to measure the frequency of the K_α-line in different elements. The huge piece of work he carried out led to a very important result. It was found that the frequency of X-rays varies from element to element in a very regular manner and in full accord with equation (6). For comparison with this equation, it is convenient to show the results of the measurements in the form of a graph,

plotting the values of $\sqrt{\frac{\nu}{R}}$ on one axis, and the atomic number Z on the other. Such a graph is given in Fig. 11.

From this graph it is readily seen that the square root of the frequency of the K_α-lines of X-rays varies linearly

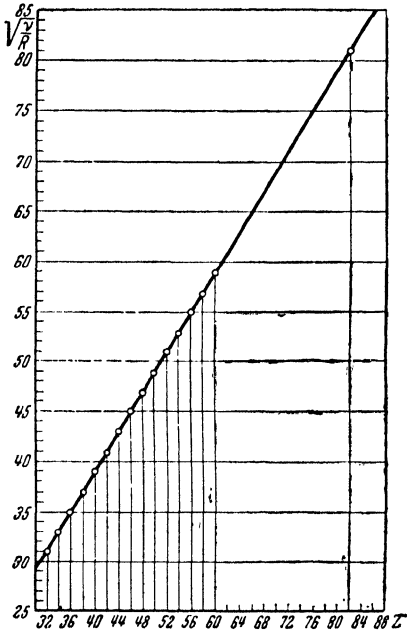


Fig. 11. The frequency of the K_α-line as a function of atomic number. The atomic number is plotted on the horizontal coordinate, and the square root of the frequency divided by the constant R on the vertical coordinate.

with the atomic number. This fact, when correlated with equation (6), signifies that the atomic number of an element is connected with the charge of the nucleus and varies just as the nuclear charge does. This remarkable result has a dual significance. On the one hand, it is a substantiation of the Bohr theory of the atom that is based on Rutherford's nuclear model, and consequently, serves as additional con-

firmation of this model. On the other hand, it enables us to measure the charges of atomic nuclei. To do this, it is necessary, according to equation (6), to measure the frequency of the K_α-line of the element under study and divide it by the constant R; then extract the square root of this ratio and add unity to the result obtained. This number will then be the magnitude of the nuclear charge.

Moseley's measurements showed that the nuclear charges of atoms of different elements coincide, with a big degree of accuracy, with the value of the atomic number. This once again confirmed the above hypothesis.

As a result of extensive work carried on by many scientists we have obtained undoubted proof that atoms consist of atomic nuclei and electron shells. The atoms of different elements differ in the size of the nuclear charge and the number of extra-nuclear electrons. It has also been established that the elements in Mendeleyev's Periodic Table are arranged in the order of increasing nuclear charge of the atoms, two adjacent elements differing by unit charge.

The existence of atomic nuclei ceased to be a hypothesis. It became a scientific truth.

Chapter III

THE MASS OF ATOMIC NUCLEI

The experiments described in the preceding chapter proved the existence of atomic nuclei and at the same time established two of their fundamental properties.

1. The size of the nuclear charge is equal to the atomic number of the element.
2. The mass of the atomic nucleus is close, in magnitude, to the mass of the whole atom.

However, in the above-mentioned experiments, the mass of the atomic nuclei was not measured directly; it was only surmised in terms of indirect data. But after the charge, the mass is the most essential characteristic of the nucleus. Thus arose the problem of measuring the mass of atomic nuclei with greatest possible precision. It is of course difficult to measure directly the mass of the nucleus. To do this, one would have to get rid of all the electrons of the atom. And this can be done only on rare occasions (for example, in the case of hydrogen and helium, where the number of electrons is small). For this reason, one has to be content with establishing the mass not of the nucleus, but of the atom as a whole. Since we have a relatively good knowledge both of the mass of an individual electron and of the total number of electrons in the atom, we are able to determine the mass of its nucleus by deducting the mass of the electrons from the total mass of the atom.

Measuring the Mass of an Atom

To determine the mass of an atomic nucleus it is sufficient to measure the mass of a separate atom. But how is this done? The simplest way would be to weigh a suffi-

ciently large but well-known number of atoms. This was the method commonly used earlier in determining the mass of atoms. It was known that one gram-atom of any substance contains $N = 6 \times 10^{23}$ atoms. One gram-atom also contains as many grams of weight as there are units in the atomic weight of the given element. Consequently, the mass of one atom is $\frac{A}{N}$ (where A is the atomic weight). This means that a determination of the mass of an isolated atom may be reduced to measuring the atomic weight.

Methods for determining the atomic weight had long since been worked out. Taking the atomic weight of oxygen as 16 and establishing by experiment the weight quantities of the interacting oxygen and the given element, it is possible to compute the atomic weight of the element.

Let us agree to express the mass of the atom not in grams but in conventional units of mass, in which the mass of an atom of oxygen is 16. In these units the mass of the atom and the atomic weight are expressed by one and the same number. Hereinafter we shall express the mass of an atom in precisely these units (the unit of mass we have selected is equal to 1.66×10^{-24} g.).

It was the relation between the atomic weight and the mass of an atom that was used in the first determinations of atomic mass. However, this method of determining the mass did not satisfy scientists. First, the accuracy of measurement of atomic weights was not very great; secondly, the number of atoms in one gram-atom was not known with sufficient accuracy, and finally, and this was most essential, it had not been proved that the masses of all atoms of a given element are alike. And what is more, a study of radioactive substances and the products of their transformations pointed to the existence of isotopes, atoms with the same chemical properties but of different mass. And not only radioactive elements have isotopes. It was found that the stable element of lead has isotopes. It might be expected that also other stable elements consist of isotopes. But to decide this question methods had to be found of measuring directly the masses of individual atoms.

Separating the Isotopes of Neon

To determine the mass of individual atoms, Thomson used the electromagnetic method, described above, of determining the ratio of the charge of a particle to its mass. If we know the size of the charge of an ion and have determined the ratio of the size of the charge to the mass of the ion, it is possible to calculate the mass of a separate ion, and, hence, also the atom. The determination of the ratio of charge to mass is based on the difference in action exerted on a moving ion by electric and magnetic fields.

If in the path of a beam of ions that has passed through an electric field and a magnetic field,* which coincide in direction, we interpose a photographic plate capable of recording the point of encounter of the ions and the plate, we should then obtain on this plate a certain curve, the position of which would depend on the mass of the ion. It may be recalled that the deflection of an ion under the action of an electric field E is

$$s_E = \frac{e}{m} E \frac{l^2}{2u^2} \tag{1}$$

and under the action of a magnetic field H is

$$s_H = \frac{e}{m} H \frac{l^2}{2u} \tag{2}$$

where e is the ion charge, m its mass, and l the amount of deflection.

Let the deflection due to the electric field be directed vertically up (Fig. 12) and the deflection due to the magnetic field, horizontally from left to right. For all ions of equal mass the deflection will depend only on the speed of the ions. However, this dependence in the case of deflection in the electric and magnetic fields differs. If, for example, the speed of the ions is one half, then in passing through the electric and magnetic fields the ion will deviate upwards four times as strongly (the action of the electric field) and only twice as strongly to the right (the action of the magnetic field).

* If the direction of the electric and magnetic fields are the same, their action on a moving charge will be mutually perpendicular.

When a beam of different-speed ions passes through the magnetic and electric fields, these ions will make impact on the photographic plate at a number of points located on a single curve (Fig. 12).

Thomson analyzed the relation of the electric and magnetic deflections and showed that the curve along which ions of a definite mass and charge but of different speeds

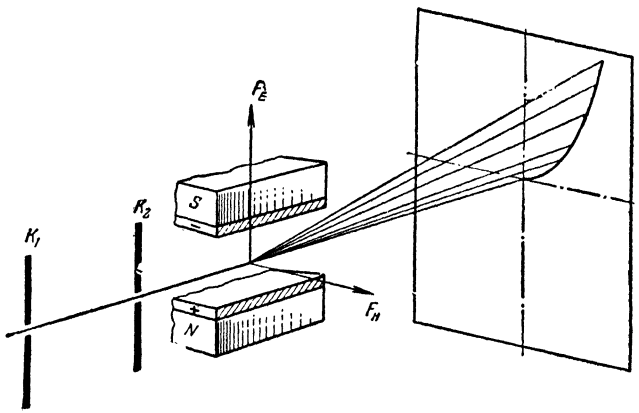


Fig. 12. A beam of ions having different speeds is broken down into a parabola by means of electric and magnetic fields. The acting force of the electric field is designated by F_E, the acting force of the magnetic field by F_H; K_1 and K_2 are diaphragms that collimate the beam.

distribute themselves is a parabola. There will be as many different parabolas as there are ions in the beam with different masses or charges. Thomson's method became known as the "parabola method," from the name of the curve.

The element selected for the first experiments was neon. The instrument used to weigh the neon ions is shown diagrammatically in Fig. 13.

Within a spherical glass bulb *A* are two electrodes *B* and *D* which are capable of exciting an electric discharge in the bulb. To enable a discharge to develop, it was necessary to evacuate the air from the bulb. This was done through a branch pipe *F* connecting the bulb *A* with a system of

vacuum pumps. Neon was injected into vessel A through a capillary tube E in order to obtain neon ions. The pressure of the neon in vessel A was regulated on the one hand by the speed of its flow through the capillary tube and on the other hand by the speed of evacuation of the gas by vacuum pumps. By selecting an appropriate relation in the speeds of these two processes, it was possible to attain the re-

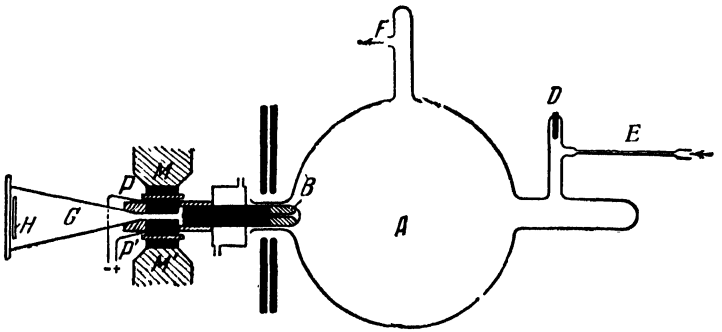


Fig. 13. Diagram of a mass-spectrograph d esigned by Thomson.

quisite degree of rarefaction of neon in vessel A for discharge to take place. A negative pole was connected to electrode B, and a positive pole to electrode D. As a result, the stream of positive ions produced during the discharge should move from electrode D to electrode B. A "canal" was drilled in electrode B to pass a certain portion of the ions into the other part of the apparatus in the form of a pencil. Here they passed between the poles of a strong electromagnet. Plates P and P' (properly insulated and with an electric field between them) were attached to the pole pieces M and M' of the electromagnet. Since the plates P, P' were parallel to the pole surfaces M, M', the magnetic and electric fields had the same direction (as is shown in the diagram in Fig. 12).

The beam of ions deflected by the magnetic and electric fields passed into the part of the apparatus labeled G in Fig. 13. Here it encountered the photographic plate H, placed perpendicular to the axis of the canal drilled in electrode B.

The photograph produced in these experiments is shown in Fig. X (see Appendix).

This figure clearly shows that the ion beam that has passed through canal B is not uniform. This resulted in not one but several parabolas. After a thorough analysis of all the obtained tracks Thomson found the parameters of these parabolas and from the former he determined the ratio $\frac{e}{m}$, from which he found the mass of the ions.

He obtained the following mass values: 200, 100, 44, 28, 22, 20. What do these numbers imply? What substance do ions of mass 200 represent?

A glance at the Periodic Table at the end of the book will give the answer at once. In square No. 80 we find mercury with an atomic weight of 200.61. It is quite natural to ascribe to atoms of mercury the mass of 200. This is all the more natural since there should be mercury vapour (from the mercury pumps) in the discharge tube. Besides mercury vapour, one should expect the presence of carbon oxides that get into the discharge tube from the lubrication used for the vacuum packing. The 44 and 28 masses correspond to ions of carbon oxides. Mass 44 consists of ions of carbon dioxide gas CO_2^+, and that of 28 belongs to the ions of carbon monoxide CO^+. The mass of 100 units was attributed to doubly charged ions of mercury, because the ratio e'/m in the case of a double charge $e'=2e$ is the same as the ratio of a singly charged ion to a mass half as much:

$$\frac{e'}{m}=\frac{2e}{m}=\frac{\frac{e}{m}}{2}.$$

Ions of mass 20 should be ions of neon although the atomic weight of neon is actually slightly more, namely 20.183. Now what are the ions of mass 22?

There is no element in the Periodic Table with this atomic weight. Thomson surmised that ions of mass 22 also belong to neon, and that, consequently, there exists not one but two kinds of neon. One kind of atoms has a mass of twenty, and those of the other kind a mass of twenty-two. Subsequently, more detailed measurements showed that there exists (true, in small quantity) yet a third isotope of neon with a mass of 21.

The atomic weight of neon is 20.183. According to Thomson this figure represents the mean weight of a mixture of two (in actuality, three) isotopes of neon. It is worthy of note that in Thomson's measurements the atomic weight of both isotopes is expressed by a whole number, 20 and 22. To obtain the mean atomic weight 20.183 from the masses of such isotopes it is sufficient to assume that the mixture contains 91 per cent of an isotope of mass 20 and nine per cent of an isotope of mass 22.

More precise measurements carried out at a somewhat later date showed neon to have the following isotopic composition:

$$Ne^{20} \ldots 90.51\%$$
$$Ne^{21} \ldots 0.28\%$$
$$Ne^{22} \ldots 9.21\%$$

(here, the superscript of the chemical symbol Ne denotes the mass number of the isotope).

In future we shall call the isotopic weight that atomic weight which an element would have if it did not consist of a mixture of isotopes, but only of the given isotope.

From his work, Thomson drew two important conclusions:

1. The element neon (and possibly other chemical elements) consists of a mixture of isotopes.

2. The isotopic weights are expressed by numbers that are very close to integers.

To the second conclusion we shall return further on; now let us examine other experiments that confirmed the first of Thomson's conclusions.

If this conclusion is correct and neon is indeed a mixture of isotopes of atomic weights 20 and 22, then why is the atomic weight of an element a constant? The point is that the atomic weight depends on the ratio of the isotopes in the mixture, and any change in this ratio should change also the atomic weight of the element. But perhaps, the atomic weight is not an exact constant? No, it is. Careful measurements carried out during investigation of this problem showed that everywhere on earth the atomic weights of elements are the same, no matter where these elements are found. However, this result does not contradict the assumption that the elements consist of isotopes, for the constancy

of the atomic weight might mean that the conditions of formation of the elements from isotopes were the same over the entire surface of the earth. To be assured of the correctness of the contention that a chemical element consists of a mixture of isotopes, and that, as an individual case, neon of atomic weight 20 and 22 exists, it was necessary to separate these isotopes or at least change their ratio. A change in the ratio of the isotopes in the mixture would change their mean atomic weight.

But how is one to change the ratio of isotopes in the mixture?

It is a relatively simple task to separate chemical elements for they behave differently in different chemical reactions. But isotopes react with all substances in the same way, and it is impossible chemically to separate them. It is true a similar task did once confront scientists; it was that of separating different noble gases, of breaking up into its constituents the mixture of noble gases—argon, krypton and xenon. The chemical properties of these gases are closely related and therefore purely chemical methods were insufficient to separate them. Use was made of differences in the physical properties of these elements, as, for instance, their atomic weights. But the atomic weight of argon is 39.9, that of krypton 83.7 and of xenon 131.3. These are very perceptible differences. Krypton is twice as heavy as argon, xenon is more than three times as heavy and still the problem of separating these noble gases was not by any means easy.

Though the difference in the atomic weights of both isotopes of neon is slight, amounting to only two units, Aston undertook to apply to the separation of these isotopes the very same procedure of diffusion used to separate the noble gases. The principle behind this diffusion method is extremely simple.

It is known that all gases possess to a greater or lesser degree the power to leak through a clay wall. This is because the molecules of a gas move in all directions and a part of them are able to diffuse through the pores of a clay wall. The greater or lesser diffusion power is due to the difference in the mass of the atoms (molecules) of the gas. The greater the mass of atoms, the lower their average speed, since the

mean kinetic energy of all molecules of a gas is the same, depending only on the temperature and not on the type of gas. Hence, a gas consisting of heavier molecules will diffuse through a clay wall more slowly than a gas that consists of lighter molecules. If we take a certain quantity of a non-homogeneous gas and allow one half of the gas to diffuse through the clay wall, there will be a slightly greater amount of light gas in the part that seeped through, and a slightly greater amount of the heavy gas in the part that remained behind.

This was the method that Aston employed. He took 100 cubic centimetres of pure neon and subjected it to diffusion fractionation, i. e., to a separation of the gas into two different parts, which separation is possible because light molecules diffuse through the clay wall faster than the heavier ones. The original portion of gas gave birth to two portions, one of which had a greater percentage of the light isotope Ne^{20}, and the other a somewhat larger amount of Ne^{22}. Or, in technical terms, as a result of diffusion there were formed two fractions, one of which was enriched with a light isotope, and the other with a heavy isotope. However, this enrichment was very insignificant and so the diffusion process had to be repeated many times.

The result of a multifold process of fractionation was two fractions of two to three cubic centimetres each, in which the ratio of the isotopes differed from normal. The atomic weight of the neon of one fraction was 20.29, of the other it turned out 20.15. Thus the first and heavier fraction contained 86% of Ne^{20} and 14% of Ne^{22}. In the second and lighter fraction the percentage was 92.5 for Ne^{20} and 7.5 for Ne^{22}. The diffusion through clay changed the atomic weight of chemically pure neon.* Thus we see that neon is indeed a mixture of isotopes.

Isotopes of Stable Elements

After the works of Thomson and Aston it became clear that not only radioactive elements consist of isotopes. In this respect, the stable elements do not differ from their

* The diffusion method was subsequently improved upon and it was possible to attain complete separation of neon.

radioactive brothers. It was now necessary to subject to a detailed and systematic investigation all the known elements. This prodigious and painstaking job was undertaken

Table IV

The Isotopic Composition of Some Elements

Atomic number	Element	Symbol	Atomic weight	Mass number of isotope	Content of isotope, %%	Atomic weight (calculated)
1	2	3	4	5	6	7
1	Hydrogen	H	1.008	1 2	99.986 0.014	1.0001
3	Lithium	Li	6.940	6 7	7.39 92.61	6.926
7	Nitrogen	N	14.008	14 15	99.62 0.38	14.003
10	Neon	Ne	20.183	20 21 22	90.51 0.28 9.21	20.187
11	Sodium	Na	22.997	23	100	—
17	Chlorine	Cl	35.457	35 37	75.43 24.57	35.491
26	Iron	Fe	55.85	54 56 57 58	5.81 91.64 2.21 0.34	55.911
29	Copper	Cu	63.57	63 65	69.04 30.96	63.619
38	Strontium	Sr	87.63	84 86 87 88	0.55 9.75 6.96 82.74	87.713
50	Tin	Sn	118.70	112 114 115 116 117 118 119 120 122 124	0.9 0.61 0.35 14.07 7.54 23.98 8.62 33.03 4.79 6.11	118.86

during the following two decades (1913-37) by a number of scientists who modified considerably the parabola method making it remarkably sensitive and precise. Fig. XI (see Appendix) gives Aston's mass-spectrograms of a number of substances. A most scrupulous analysis of the isotopic composition of a number of elements is still going on.

In Table IV are tabulated data characterizing the isotopic composition of a few elements. It contains the mass numbers of the isotopes (column 5) and their percentage content (column 6). The atomic weight of each element is indicated in column 4. Column 7 contains the value of the atomic weight computed on the basis of data concerning the isotopic composition. A comparison of columns 4 and 7 shows that agreement between the computed and measured values is good.

The greater part of the chemical elements have a complex isotopic composition. For example, tin has ten isotopes. Only a small number of elements consist of only one isotope. These are beryllium with an atomic weight of 9, fluorine of atomic weight 19, then sodium-23, aluminium-27, phosphorus-31, scandium-45, vanadium-51, manganese-55, cobalt-59, antimony-75, yttrium-89, niobium-93, rhodium-103, iodine-127, cesium-133, lanthanum-139, praseodymium-141, terbium-159, holmium-165, thulium-169, tantalum-181, gold-197, and bismuth-209.

It is remarkable that the atomic weights of all these elements that consist of only a single isotope are expressed almost exactly by whole numbers. This integer that characterizes the mass of the isotopic atoms is called the mass number. All the other elements, whose atomic weights are not expressed by whole numbers, were found to consist of a mixture of isotopes, each of which has an integral atomic weight. This is a fundamental result, the significance of which will immediately be grasped from what follows.

Prout's Hypothesis

Let us return for a moment to the early nineteenth century when atomic weights were measured very crudely, and for only a few elements at that. At the time (1816),

Prout noticed that the known atomic weights measured by Dalton were expressed as whole numbers and suggested the hypothesis that all elements consist of atoms of hydrogen in quantities that correspond to their atomic weights.

Prout's hypothesis was soon forgotten for Dalton's measurements were found to be erroneous. The actual atomic weights of many elements differ very sharply from whole numbers. An illustration is chlorine with an atomic weight of 35.45, magnesium of atomic weight 24.32, nickel (atomic weight 58.69), zinc (atomic weight 65.38) and so forth.

However, when the investigations of Thomson, Aston and other workers showed that the atomic weights of the isotopes of all elements are really whole numbers and it was found that the reason for the departure of mean atomic weights from the integral value lay in the existence of isotopes, the hypothesis calling for all elements to be built up from hydrogen was revived. Of course, there could be no talk of taking this hypothesis in Prout's formulation. Our knowledge concerning atoms had changed immensely during those hundred years that had elapsed since the origin of this hypothesis. By the time Aston completed his work the nuclear model of the atom had received sufficient experimental confirmation and was generally accepted. If one takes the stand of Prout and considers the integral values of the atomic weights to mean that the chemical elements are composed of the more simple elements, such as hydrogen, then the following may be inferred:

1. The primordial atomic nucleus is that of the hydrogen atom.

2. The nuclei of all the remaining elements are built up from hydrogen nuclei and therefore the nuclear masses (hence also the atomic weights of the elements) must be multiples of the mass of the hydrogen nucleus.

In view of the position which the atomic nucleus of hydrogen occupies in this system, it was given a special name, "proton," which means first.

Thus, the nuclei of all atoms are made of protons. But it is quite obvious that such a hypothesis is not sufficient. Indeed, a look at the Periodic Table shows us that hydrogen is followed by helium of atomic weight 4. Consequently, the helium nucleus should consist of four protons. But the

proton (the hydrogen nucleus) is positively charged. The size of its charge is numerically equal to the charge of an electron, that is, the elementary unit, therefore, the helium nucleus should have a charge equal to four elementary units. But the atomic number of helium (i. e., its place in the Periodic Table) is two, which means that the charge of its nucleus is not four but two elementary units. Or take, for example, another element, aluminium with its atomic weight 27. Its nucleus should contain twenty-seven protons, but then the charge of its nucleus should equal twenty-seven elementary units, whereas in actuality the atomic number of aluminium, and hence also its charge, is thirteen. This discrepancy is the same for all the other elements of the periodic system too.

It is clear that the above stated hypothesis is insufficient and must be supplemented. It was suggested that atomic nuclei might contain electrons in addition to protons. The presence of electrons with their negative charge would naturally reduce the positive charge created by the protons of the nucleus. And then the total charge of the nucleus would be less than the over-all charge of all the nuclear protons. It is quite a simple matter to figure out how many protons and electrons there should be in a nucleus to make its mass and charge of the proper value.

Let the atomic weight of the isotope be A, and its atomic number, and hence also the nuclear charge, Z. If the atomic weight is A, there are then A protons in the nucleus, i. e.,

$$N_p = A$$

where N_p denotes the number of protons. If the nuclear charge is Z, then the following relation must be fulfilled:

$$Z = N_p - N_e; \quad N_e = A - Z,$$

where N_e is the number of electrons in the atomic nucleus. On these assumptions it was possible to formulate as follows our conception of the atomic nucleus: all nuclei consist of protons and electrons. The number of protons is equal to the mass number of the isotope, and the number of electrons is equal to the difference between the mass number and the atomic number.

It is difficult to name another hypothesis that received such rapid and immediate recognition. After the discovery of isotopes and the establishment of the integrality of the atomic weight, this hypothesis seemed so natural that it was expressed at once by a very large number of physicists. The atomic nucleus could not be a simple system. The very existence of radioactivity indicated that nuclei were complex systems, and it was of course the most natural thing to think that they consist of protons and electrons. However, in time this hypothesis had to be given up.

The Binding Energy of Nuclei

From the above it is clear of what great significance was the knowledge of the isotopic composition and the numerical values of atomic and isotopic weights. The natural desire arose to determine these important values with the greatest possible precision.

The atomic weights and isotopic composition were measured with extraordinary intensity during the years from 1930 to 1940. A number of workers succeeded in improving considerably the method of deflection in electric and magnetic fields.

We are not in a position here to dwell in detail on this interesting and instructive work of the physicists. To illustrate the results attained, we give in Table V the atomic weights of several isotopes. It should be borne in mind that the atomic weights are computed with respect to oxygen, that is, the atomic weight of the isotope "oxygen-sixteen" is taken as being exactly equal to 16 units.* In addition to the atomic weights, Table V also gives the size of the error of this determination. As may be seen from the accompanying table, the accuracy which it was possible to attain in determining the mass of the atom (recall that the unit of mass which we selected expresses by one and the same number both the mass of the atom and the atomic weight) proved

* There are two atomic weight scales: the "physical" scale, in which the atomic weight of the isotope oxygen-16 is taken as 16 units, and the "chemical" scale, in which the atomic weight of the element oxygen is taken as 16 units.

very considerable, of the order of several ten-thousandths of one per cent. This precision in the measurements of the atomic masses led to the establishment of several important relationships.

First of all, note that in the units agreed upon, the atomic weight of hydrogen proved not exactly equal to unity, but slightly (by eight-thousandths) greater than unity. Likewise, the atomic weights of the other elements depart slightly from whole numbers. Since we agreed that:

1) the atoms of all substances consist of protons and electrons; and if A is the integer closest to the atomic weight (the mass number), then the atom contains A protons and A electrons, of which Z electrons are extra-nuclear, and A-Z electrons enter into the atomic nucleus;

2) the atomic weight of hydrogen is not exactly equal to unity, the atomic weight of the elements should not, in fact, be absolutely integral. It should only be A times greater than the atomic weight of hydrogen. Actually this was not the case.

Look at Table V that contains the atomic weights of several isotopes (isotopic weights). Take, for instance, helium of atomic number 2 and with an atomic weight close to four units. Helium thus consists of four protons and four electrons (two in the nucleus and two outside). The weight of the atom is made up of the weight of the four protons and four electrons. But the weight of one proton and one electron is the equivalent of the atomic weight of hydrogen; therefore we should expect the atomic weight of helium to be exactly four times that of hydrogen. But the four-fold atomic weight of hydrogen equals 4.03252, whereas that of helium is 4.00386, that is, less by 0.02866. This difference in atomic weights exceeds appreciably the measurement error, which in this instance is only 0.00003.

Thus, *the atomic weight of helium is not exactly equal to four times the atomic weight of hydrogen, but is somewhat less.*

But why?

Let us take a similar case. We know very well that water consists of hydrogen and oxygen. Two atoms of hydrogen and one of oxygen combine to form one molecule of water. However, the formation of water is never the sole result

Table V

Atomic Weights of Some Isotopes

Element	Symbol of isotope	Atomic weight
1	2	3
Hydrogen	$_1H^1$	1.008131±0.0000033
	$_1D^2$	2.014725±0.0000064
Helium	$_2He^4$	4.003860±0.000031
Lithium	$_3Li^6$	6.016917±0.000051
	$_3Li^7$	7.018163±0.000057
Beryllium	$_4Be^9$	9.014958±0.000062
Boron	$_5B^{10}$	10.016169±0.000070
	$_5B^{11}$	11.012901±0.000050
Carbon	$_6C^{12}$	12.003880±0.000025
	$_6C^{13}$	13.007561±0.000043
Nitrogen	$_7N^{14}$	14.007530±0.000016
	$_7N^{15}$	15.004870±0.000072
Oxygen	$_8O^{16}$	16.000000
	$_8O^{17}$	17.00450 ±0.000060
	$_8O^{18}$	18.00485 ±0.00018
Neon	$_{10}Ne^{20}$	19.99889 ±0.000061
Sodium	$_{11}Na^{23}$	22.99644 ±0.00018
Aluminium	$_{13}Al^{27}$	26.99069 ±0.00043
Silicon	$_{14}Si^{30}$	29.98290 ±0.00015
Sulphur	$_{16}S^{32}$	31.98252 ±0.00026
Chlorine	$_{17}Cl^{35}$	34.97884 ±0.00019
Chromium	$_{24}Cr^{50}$	49.96020 ±0.00025
Manganese	$_{25}Mn^{55}$	54.95545 ±0.00027
Copper	$_{29}Cu^{65}$	64.948884±0.00032
Strontium	$_{38}Sr^{86}$	85.93533 ±0.00043
Zirconium	$_{40}Zr^{90}$	89.93178 ±0.00063
Cadmium	$_{48}Cd^{110}$	109.93873 ±0.00066
Tin	$_{50}Sn^{116}$	115.93779 ±0.00058
Barium	$_{56}Ba^{138}$	137.9491 ±0.0011
Hafnium	$_{72}Hf^{180}$	180.0004 ±0.0014
Platinum	$_{78}Pt^{194}$	194.0256 ±0.0014
Lead	$_{82}Pb^{208}$	208.0422 ±0.0015

of this combination of atoms of hydrogen and oxygen. Heat is always evolved in the process. This reaction heat, which is otherwise called the binding energy of the molecule, characterizes the force that binds the atoms in the molecule. The greater the amount of heat evolved in the formation of a molecule (the greater the binding energy of the molecule), the more firmly are the atoms bound and the harder it is to

break up such a molecule. The very same thing should take place in the case of atomic nuclei, which are complex formations. On our hypothesis, a helium nucleus is formed from four protons and two electrons. These six particles combine to form a very stable body, the atomic nucleus of helium. Since protons and electrons form a stable combination, a certain amount of energy should be released during the formation of a nucleus of helium. The quantity of such energy will be the greater, the more stable the combination.

In the formation of one gram-molecule of water, 68,000 calories are evolved. Of course, a nucleus of helium is immeasurably stronger than a molecule of water and therefore it is natural to expect that considerably greater energy will be produced in the formation of one gram-molecule (or, to be more precise, one gram-atom) of helium.

But what connection is there between this and the difference in the atomic weights of helium and hydrogen which we detected above? The answer is: a most intimate one.

In order to make clear the relation that exists between the heat of a reaction and the fact that the atomic weight of helium is slightly less than the four-fold value of the atomic weight of hydrogen, let us examine a rather prevalent delusion.

Sometimes even today the definitions of mass and energy are given independently of each other. The mass is determined from the Newtonian laws of motion (as a measure of the inertia of a body) as a value independent of the character of motion (and hence, of the velocity). Energy is defined as the ability to do work. This is due to the fact that for a long time mass and energy were considered independent properties of matter. It was believed that there exist two independent physical laws. One, the law of the conservation of mass, the other, the law of the conservation of energy. However, experiment and theory (Einstein's theory of relativity) show that this is not so, and that mass is in fact not independent of energy.

In 1901 Kaufmann, determining the relation of the charge of an electron to its mass found that this relation, which is constant (within measurement error) for slowly moving electrons, begins to change when their speed approaches that of light. Later he established that the variation of the

charge-to-mass ratio of the electron with its speed is in complete accord with the conclusions of the theory of relativity.

On this theory, the dependence of mass on velocity is expressed by the following equation:

$$m=\frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}, \qquad (7)$$

where m_0 is the rest mass of a body, m the mass that it has when moving with a speed v, and c is the velocity of light (3×10^{10} cm./sec.)

At ordinary speeds this change in mass is so negligible that it cannot be detected. Take, for example, an artillery shell. As we know, it shoots out of the muzzle of the gun with an initial speed of 1,000 metres per second At this speed its mass will change only by 10^{-11} of its original value. It is impossible to detect such an insignificant change in mass. Even if the shell were ejected at a speed of 10,000 m /sec., its mass would still be far too small to measure; it would amount only to a ten-millionth of one per cent. However, for electrons (cathode rays) the speed of which reaches values of 10^9-10^{10} cm. / sec., the change in mass turns out to be of measurable magnitude. Consequently, mass is not a constant value, independent of the velocity (the energy of motion); it does depend on the velocity and is obviously related in some way to energy.

The theory of relativity establishes this relation in a very definite manner. According to this theory, the relation between energy and mass is written as

$$E=mc^2. \qquad (8)$$

In this equation E is the energy, m the mass, and c the velocity of light.

This connection between energy and mass remained a long time undetected for the simple reason that the energies dealt with theretofore were relatively small. Thus the mass connected with the thermal energy generated in the burning of a whole trainload of coal amounts to only about half a gram. According to equation (8) one calorie corresponds to a mass of 4.67×10^{-14} gram. Quite naturally, such a small mass could not be detected.

It was precisely the fact that the energies that we have for so long been accustomed to in our "terrestrial" practice were very small, that the relation between mass and energy had escaped investigators. A false impression was created and strengthened that mass and energy are independent values, and that the mass of a moving body does not depend on its velocity.

As our acquaintance with phenomena occurring in atoms and atomic nuclei increases we more and more come into contact with high speeds and with energies materially greater than those encountered in our everyday life. For this reason, we must not for an instant forget about the relation that exists between mass and energy.

In the light of these facts, the reason for the atomic weight of helium being less than the quadruple atomic weight of hydrogen is obvious. And this, strictly speaking, was to be expected because everything that we know about atomic nuclei is evidence that it is extremely difficult to act on them. Atomic nuclei are very stable systems. Therefore, during their formation, *a large quantity of energy should be released.* And the mass of the system (and with it the atomic weight) should diminish perceptibly. The difference

$$\Delta A = 4A_{\mathrm{H}} - A_{\mathrm{He}} = 0.02866$$

which we found, therefore characterizes the building energy of the nuclei of helium, or, in other words, the binding energy of the particles that make up this nucleus.

Is this energy great?

Using equation (8) we find that a mass of 0.02866 gram lost in the building of one gram-atom of helium corresponds to 6.2×10^{11} calories. If we wanted to obtain this energy by burning coal we should have to burn five to six carloads of the best Donets anthracite in order to reach the energy value released in the formation of one gram-atom (four grams) of helium. But does a helium nucleus really consist of four protons and two electrons?

We will soon give an exhaustive answer to this question, but for the present let us return to the problem of the mass of atomic nuclei and the separation of isotopes.

The development of methods of analysis of isotopic atomic weights made it possible, by weighing individual atoms, not only to show that the ordinary chemical elements are a mixture of isotopes of different atomic weight, but also to determine this weight with an accuracy that exceeded by far the ordinary methods of determining atomic weights. Such precise knowledge of nuclear mass enabled us to detect and measure the mass a nucleus loses as a result of the energy release during its formation. This diminution of mass characterizes the *nuclear binding energy*. The binding energy is a most important physical characteristic of the nucleus; this explains the importance of more and more precise measurements of the atomic weights of isotopes.

Methods of Separating Isotopes

Let us now examine the problem of the separation of isotopes. The discovery of isotopes of stable (non-radioactive) elements led to numerous attempts to separate them. We have already mentioned the diffusion method used by Aston to attain at least a partial separation of the isotopes of neon. And we saw what labours it involved. The gas had to be driven through a clay barrier many dozens of times. The process of distillation progresses slowly and the degree of enrichment is insignificant.

The diffusion method of separation was subsequently improved upon. High-vacuum pumps were used to create a highly evacuated space on one side of the clay barrier, thus noticeably speeding up the diffusion process. On the other hand, pumps were used to feed back into the system the impoverished fraction. In this way, the quantity of gas undergoing separation did not diminish. In addition, special barriers with a considerably larger number of microapertures than are to be found in clay barriers began to be used for diffusion. And this also materially speeded up the diffusion process.

The use of a large number of pumps and special porous barriers as well as the creation of a constantly operating apparatus improved conditions for the separation of isotopes to such an extent that two fractions were obtained from

ordinary neon which, as it will be recalled, contains 9.2 per cent of Ne^{22}: a heavy fraction with $2^1/_2$ times as much Ne^{22} as Ne^{20} and a light fraction with less than one per cent of Ne^{22}. The difference in the atomic weights of both fractions reached a tremendous figure, 1.4.

Another method of isotope separation that has been used recently with great success, is the method of thermal diffusion. The phenomenon of thermal diffusion consists in this: if a constant difference of temperature is established in a homogeneous mixture of two gases, then due to the diffusion processes that arise, there takes place a separation of this mixture into layers, with one of the components predominant in the cold section and the other in the hot. As to which of the components of the mixture will dominate the hot section, depends on the type of interaction of the molecules. Usually, the heavy molecules are more prevalent in the cold section, whereas the light dominate the hot section, though there are mixtures that behave in just the opposite way with heavy molecules in the majority in the hot section and light ones in the cold. This phenomenon was used to separate isotopes.

Other phenomena that develop as a function of the speed of the molecules may also be used to separate isotopes. For this purpose, use may be made of electrolysis, centrifuging, the evaporation of molecules at low pressure, etc.

Of course, it is also possible to employ the method of magnetic and electric deflection which is used to measure mass. This method is good in that it permits immediate separation of one isotope from another and not only increasing the concentration of one of the isotopes in the mixture.

This method was used, for example, to separate the isotopes of lithium, potassium and uranium. But its efficiency was low. It took 24 hours to obtain one milligram of lithium, and three hours to obtain 1.8 micrograms of U^{238}. The efficiency limitation in the separation of isotopes was due to the fact that the ion current could not be made very big. When the density of the ions becomes large, repulsive forces between them begin to take effect perceptibly (it may be recalled that by Coulomb's law like charged particles repulse one another). The more ions there are in motion at

once, the greater are the forces of repulsion that arise between them. The ion paths are distorted, and the isotopes do not separate.

Recently, however, methods have been found to eliminate this detrimental influence of ions jostling each other. This has enabled a very effective separation of isotopes to be attained by magnetic and electric deflections.

The difficulty of isotope separation is due to the fact that the relative difference in the isotope masses is small. In the case of neon, for example, it is five per cent, of uranium, about one per cent.

There is, however, one case in which the relative change in the mass of the isotopes proved exceedingly great. It was here, of course, that the first effective results were achieved.

Separating the Isotopes of Hydrogen

The history of this separation is instructive. In the system of atomic weights, that of oxygen is taken as 16. The atomic weight of hydrogen differs from unity. Measurements carried out rather accurately by different workers give 1.00777 as the atomic weight of hydrogen. This figure does not coincide with the ratio of the atomic weights of oxygen and hydrogen as measured by Aston with the aid of the mass-spectrograph.

It is precisely from Aston's findings that it follows that the ratio of the atomic weight of hydrogen to that of oxygen is such that if the weight of an atom of oxygen-sixteen is taken as 16 units, the weight of an atom of hydrogen will come to 1.00756. The difference between the two figures is slight, only in the fourth decimal place, still it is a real difference because it goes beyond the limits of experimental error.

The discrepancy between these different methods of measuring one and the same value could arise only because the methods were used to measure something that was not exactly the same. Indeed, Aston measured the ratio of the weights of oxygen-16 to hydrogen-1; whereas the chemists measure the ratio of the average atomic weights of oxygen and hydrogen. True, it was believed that neither oxygen nor hy-

drogen had any isotopes, or rather that each of them consisted only of one isotope. But what if this was not the case? What if both these isotopes or at least one of them contained an admixture of other isotopes, but in exceedingly minute quantities?

It is impossible to detect the existence of such isotopes, and hence it was not possible to take account of the influence exerted by the presence of this weak isotope on the average atomic weight of the element. For this reason, the discrepancy indicated above between the two measurements might be a consequence of minute quantities of admixtures of other unknown isotopes.

And true enough, as early as 1929, the isotopes of oxygen of atomic weight 17 and 18 were discovered. As was expected, the content of these isotopes proved exceedingly small. To every ten thousand atoms of oxygen-16 there were four atoms of oxygen-17 and twenty atoms of oxygen-18.

However, the discovery of the isotopes of oxygen did not eliminate the foregoing discrepancy. If we take into account the actual isotopic composition of oxygen and agree that 16 is not its average atomic weight, but the weight of the isotope oxygen-16, then the atomic weight of hydrogen will turn out 1.00799 and not 1.00777. The correction for the multi-isotopic composition of oxygen proved small, and this not only failed to improve the situation, it made it worse, for on Aston's findings the atomic weight of hydrogen even so was less than that from chemical data, and after the correction it became still less. Taking note of this fact physicists decided that probably hydrogen itself was not a pure element but consisted of a mixture of two or a larger number of isotopes. Since the chemical atomic weight of hydrogen, which is an average atomic weight, proved greater than the atomic weight of hydrogen-1, which was determined by Aston, it was to be expected that hydrogen was a mixture of heavier isotopes. If we assume that the discrepancy in the atomic weights (the chemical weights and those measured by Aston) is due to the presence of an isotope of hydrogen of mass two then to explain this discrepancy only 0.2 per cent of an admixture of the hydrogen isotope with the double atomic weight would be sufficient. Having established this, physicists set out in the search

for heavy hydrogen. The first method was that of evaporating hydrogen at low pressure. They first evaporated an appreciable part of the hydrogen and subjected to spectral investigation the residue, which was thought to be enriched with the heavy isotope of hydrogen (since the light isotope had evaporated to a greater extent). Besides lines belonging to ordinary hydrogen, new lines were discovered which, according to calculations, were those that hydrogen should emit if its mass were two and not one.

It was thus proved that there really does exist a heavy isotope of hydrogen with an atomic weight of two.

The heavy isotope of hydrogen subsequently received a special name, "deuterium." To distinguish the light isotope of hydrogen with its chemical symbol H, deuterium is designated by D. In these symbols, the formula of heavy water (in the molecules of which both atoms of hydrogen are of the heavy variety) becomes D_2O. The discovery of the heavy isotope of hydrogen played a big role in the study of the atomic nucleus. This role will be discussed in a later chapter.

The discovery of deuterium was of no less importance in the study of the phenomenon of isotopy itself, for it was here that scientists first encountered a case when the mass of one isotope is twice that of the other, and for this reason, the influence of mass on the development of physical phenomena should in the case of an isotope of hydrogen be especially clear-cut. And true enough it was soon found that in electrolysis there takes place an extremely intensive enrichment with the heavy isotope of hydrogen.

This discovery was utilized by Lewis. He subjected acids to a prolonged and repeated electrolysis, and obtained several grams of nearly pure heavy water.

Heavy water differs from light water in many of its physical properties. Its molecular weight is 20 and not the 18 of ordinary water, and its density is greater than that of ordinary water, 1.11. Heavy water freezes at 3.8°C. and not at zero. It boils at 101.42°C. instead of 100°C. Ordinary water has a maximum density at 4°C.; again heavy water is different, its maximum density is reached at 11.6°C. The refractive index of light for heavy water is less than for ordinary water. We see that many of the physical proper-

ties of heavy water are noticeably different from those of ordinary water. The sharpest divergence was noted in the biological properties of heavy and ordinary water. It was found that in heavy water seeds do not germinate, and microbes, tadpoles and fishes die. Apparently, the change in the speed of the water molecules which is due to the altered mass of the molecules, changes so radically the kinetics of the vital processes that their normal course becomes impossible.

The process of separating heavy and light hydrogen has at present been perfected to such a degree that it has become possible to obtain "pure" heavy water. The spectrum of the water vapours does not at all exhibit the lines of light hydrogen. The only spectral lines visible are those of heavy hydrogen.

The obtaining of heavy hydrogen played a big role in science. It led to the formation of new divisions in biology, chemistry and physics and has contributed to the development of nuclear physics.

Chapter IV

THE DISINTEGRATION OF ATOMIC NUCLEI

The year 1919 will always remain a milestone in the history of science. In that year Rutherford first accomplished and observed the artificial disintegration of atomic nuclei. This discovery is not one of those accidental observations so common in the history of science. The whole line of development of our knowledge concerning atomic nuclei called for these experiments.

Let us review briefly the state nuclear science had reached by 1919.

The experiments of Rutherford and other workers had unquestionably established the existence of atomic nuclei and their role in the individual properties of atoms.

Radioactivity, the identity established between alpha particles and the nuclei of helium atoms, the transformation of radium into an emanation (radon), as well as a long series of other radioactive transformations showed clearly that atomic nuclei are complex formations and that a large number of nuclei have the same structural elements. It might be expected, for example, to find alpha particles in many nuclei, for instance in the nuclei of uranium I, uranium II, ionium, radium, radon, radium A, polonium, thorium, radiothorium, thorium X, thorium emanation, protactinium, etc., for in the process of radioactive decay all these substances emit alpha particles.

Radioactive transformations showed that the chemical elements are not eternal and immutable and that they are capable of mutual transmutation. This could also serve as a confirmation of the view that structurally the various atomic nuclei have many features in common.

And finally the discovery of the existence of isotopes with atomic weights that are multiples of the atomic weight of hydrogen was almost conclusive proof that all nuclei are built up of the same elementary units, representatives of which might be the atomic nucleus of hydrogen—the proton—and the atomic nucleus of helium, the alpha particle.

They might be, but are they in reality? Do all the atomic nuclei actually have protons and alpha particles? This question quite naturally was disturbing to scientists.

But how was one to penetrate into atomic nuclei and prove that they have within them such particles as, for example, protons?

It seemed that the very idea of probing the depths of the atomic nucleus was sheer fantastic dreaming since all experiments aimed at acting on nuclei even the slightest bit (to say nothing of penetrating them) had ended in complete failure.

But, as is often the case, reality surpassed by far the boldest imagination. And means were found that could act on nuclei.

Anomalous Scattering of Alpha Particles

We have already mentioned that Rutherford and his pupils made a thorough study of the scattering of alpha particles. The reader will recall that these were the experiments that led to the discovery of atomic nuclei.

They considered this phenomenon (alpha-particle scattering) to be very important and endeavoured to make as full a study of it as possible. More and more experiments were performed to verify the Rutherford law. Among them were experiments aimed at a comparison of the scattering of alpha particles at various angles by light and heavy elements. And here they hit upon a surprising phenomenon. It appeared that the scattering of alpha particles by heavy elements proceeds "normally," as is required by the Rutherford law. Whereas the scattering of alpha particles by light elements was "anomalous." The intensity distribution of alpha particles scattered in different directions by light elements proved different from what was to be expected judging from Rutherford's theory.

The natural question was: why are alpha particles scattered by heavy elements as predicted by Rutherford's theory, and why does this not hold for the light elements? The difference between the heavy elements and the light elements is this.

In heavy elements the charge of the nucleus is greater. For example, the heavy element lead has a nuclear charge of 82 units. The forces of repulsion between such nuclei and the alpha particles are exceedingly great and they force the alphas out of their paths when they are relatively far from the nucleus. The situation is different in the case of light elements. The nuclear charge of these elements is relatively small. Thus, for example, the charge of the nitrogen nucleus is only seven units. The forces that deflect alpha particles from such nuclei will be considerably less than the forces acting between an alpha particle and a lead nucleus. If such be the case, it might seem that the reason for the anomalous scattering of alpha particles by light elements lies in the fact that the alphas come too close to the nucleus and, maybe, even penetrate it.

It was the possibility of an alpha particle penetrating the atomic nucleus that led Rutherford to try to use alpha particles emitted by radioactive substances to split nuclei.

Alpha particles that shoot out of atomic nuclei with tremendous speeds, and, hence, possess enormous kinetic energy (of the order of nuclear energies, so to speak) might be these "projectiles" that are capable of breaking through the "inaccessible armour" of normal nonradioactive atomic nuclei.

To be more sure, Rutherford selected for these experiments the fastest alpha particles, those emitted by radium C'. They have a speed of 19,200 km./sec. Light elements were selected as the target of this devastating bombardment with alpha particles.

The Disintegration of Nitrogen Nuclei

The first substance with which Rutherford succeeded in achieving positive results was nitrogen.

The experimental part of these experiments was extraordinarily simple and ingenious.

Fig. 14 shows schematically the instrument used in these experiments.

A radioactive deposit formed by the decay products of radium was placed on a tiny disc D placed inside apparatus P which was filled with the gas under study. Disc D with the radioactive precipitate served as a source of alpha particles. The size of the apparatus and the pressure of the gas in it were selected so that all the alpha particles including the fastest of them would be absorbed inside the gas and could not reach wall E of the apparatus in which an opening S was

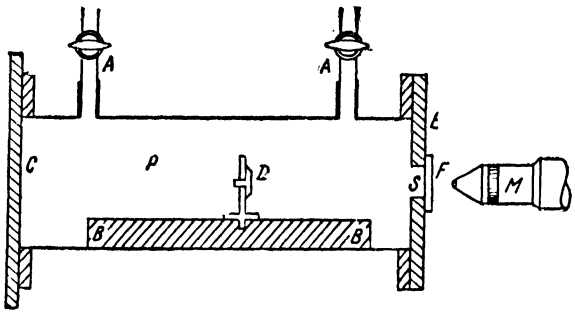


Fig. 14. Diagram of Rutherford's instrument for observing the disintegration of atomic nuclei.

made. Behind the opening was a screen F made of zinc sulphide on which, as we already know, there arise bright flashes when individual alpha particles fall on it. The window S was covered by a thin silver foil carefully pasted to the wall of the instrument to prevent any outside air from getting inside. The other end of the instrument was closed by a cover C that was sealed with special putty that prevented any exchange between the outer air and the gas inside. Using two cocks AA, one of which connected the instrument with a pump, and the other with a tank containing the gas, it was possible to evacuate the vessel and fill it with the gas to be investigated.

Fluorescence of screen F was observed with a microscope M. All observations were naturally conducted in the dark.

Rutherford's observations showed that if vessel *P* is filled with nitrogen, screen *F* will clearly exhibit bright scintillations. As we pointed out above, the alpha particles could not reach the screen and hence, they could not be the cause of the scintillations. Maybe some other unknown particles coming from the radioactive precipitate caused the scintillations. To find out, Rutherford removed the nitrogen from the apparatus and replaced it with oxygen. In this case no scintillations at all were detected. The result was the same when carbon dioxide was put in. No scintillations were visible. Thus the particles that struck the screen in the experiments with nitrogen and caused scintillations were connected not with the radioactive source but with nitrogen. When nitrogen is bombarded with alpha particles there arise some other particles that are capable of piercing 28 cm. of air.

What sort of particles are they?

To find out, Rutherford subjected them to the action of electric and magnetic fields, he measured their charge and mass and found that these particles were protons, the atomic nuclei of hydrogen.

Now where could protons have appeared from? Are they not the result of a chance admixture of hydrogen to the nitrogen? Rutherford immediately began a series of experiments that precluded this possibility completely.

First nitrogen was purified chemically. However, no matter how carefully nitrogen was purified of hydrogen, the scintillations continued, and they continued with the same intensity. Hence, the protons that he detected could not result from certain alpha particles colliding with atoms of hydrogen that by chance were among those of nitrogen, and communicating to them an energy sufficient to give rise to protons of such high energy that they were capable of producing scintillations upon impinging on a screen of zinc sulphide. If such be the explanation, then *protons could arise only from inside atomic nuclei of nitrogen.*

This was a startling discovery: in the bombardment of nitrogen by fast alpha particles, protons shoot out of the nitrogen nuclei. The energy of the protons could be computed from their range, and was found to be approximately six million electron-volts. If we recall that the greatest energy of alpha particles used to bombard nitrogen (the alpha parti-

cles of RaC') was 7,700,000 electron-volts, it will be clear that 1,700,000 electron-volts was expended in knocking one proton out of a nitrogen nucleus.

The Disintegration of Other Elements

After it had been firmly established that alpha particles do actually knock protons out of nitrogen nuclei, the new problem was to find out in what elements alpha particles are capable of doing the same thing.

Rutherford subjected to bombardment with alpha particles a large number of different substances and soon found that protons appear also in certain other cases, namely, in the bombardment of boron, fluorine, sodium, aluminium and phosphorus. In all these cases he observed the appearance of protons of range greater than that of the alpha particles participating in the bombardment. The natural question was: does not bombardment of other elements by alpha particles also give rise to protons, only of less energy. It was impossible to detect such protons even if they existed, because this would require having the screen so close that the alpha particles themselves would reach it; and it is not possible to distinguish a flash produced by an alpha particle from one produced by a proton.

To check and find out whether such "short-range" protons are produced required a new observation technique. A very simple way out was soon found that made it possible to escape the difficulties connected with the range relation between protons and alpha particles. The screen was placed at the side so that it was off the path of the alphas. But protons emerging perpendicularly to the direction of flight of the alpha particles could reach the screen, and, hence, could be detected by the scintillations they caused.

The new instrument of Rutherford and Chadwick designed for observing the detachment of protons in a direction perpendicular to the flight of the alpha particles is shown in Fig. 15. In this apparatus the screen *F* made of zinc sulphide is placed in such a way that the alpha particles emerging from plate *D* cannot impinge on it. At the same time, the protons emerging from the substance under study attached to plate

G and subjected to bombardment by alpha particles could reach screen *F* without interference and could cause scintillations. The source of alpha particles together with the irradiated plate could be moved inside the instrument, thus varying the distance between the irradiated object and the screen. These investigations showed that the disintegration

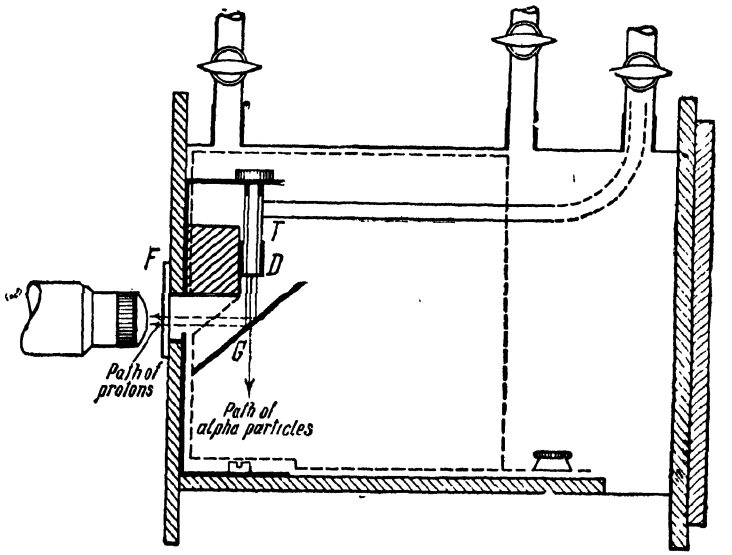


Fig. 15. The Rutherford-Chadwick apparatus for observing nuclear disintegration by alpha particles applying the right-angle method.

of nuclei (the detachment of protons) also takes place in a number of other elements. Neon, magnesium, silicon, sulphur, chlorine, argon and potassium likewise were found to disintegrate. At the same time, no disintegration was detected in any element beyond potassium in the Periodic Table. However, there were still some elements lighter than potassium that did not disintegrate. Helium, lithium, beryllium, carbon and oxygen proved to be stable elements that would not disintegrate.

The destruction of nuclei by alpha particles is an extraordinarily rare process. In the bombardment of aluminium,

seven to eight protons are observed per million bombarding alpha particles with a range of 7 cm.

With increase in atomic number the probability of nuclear disintegration diminishes. This, incidentally, is rather natural, since with the increase in atomic number the nuclear charge also increases, and with it the forces of repulsion between the alpha particle and the nucleus of the element under bombardment. In approaching a nucleus, the alpha particle is forced to spend so much energy that it hasn't enough left to dislodge a proton from the nucleus. Obviously, if the nucleus has a large enough charge the alpha particle may not even have enough energy to approach it. This is apparently the reason why Rutherford did not succeed in observing the disintegration of elements heavier than potassium.

What actually happens to an alpha particle when a nucleus splits?

Rutherford's experiments that established the disintegration of nuclei by alpha particles enable us to observe only a part of the picture. In these experiments only the behaviour of the proton can be followed. The fate of the residual nucleus and of the alpha particle itself remained unknown.

Blackett's Experiments

For a long time Blackett studied the tracks of alpha particles in a Wilson cloud chamber. He was right in thinking that the phenomenon of disintegration of an atomic nucleus should be clearly visible in such a chamber. The appearance of protons might be detected because their range is greater than that of an alpha particle and also because their ionizing power is less than that of alpha particles; and hence, they create fewer ions along their paths. For this reason, less fog will condense in the wake of a proton in the chamber than in the path of an alpha particle. The photographs made with a cloud chamber will exhibit proton tracks that are thinner than those of alpha particles.

The problem posed by Blackett proved an exceedingly difficult one. Recall that the process of disintegration of a nucleus is a very rare event. One therefore has to photograph the tracks of tens and even hundreds of thousands of alpha

particles before hitting on the happy event of nuclear disintegration. It is impossible to obtain a large number of tracks on one photograph since it will then be difficult to analyze the picture observed. The average capacity of one photograph was about twenty alpha-particle tracks. To deduce something about the character of the transformations taking place with atomic nuclei, Blackett had to make over twenty thousand cloud-chamber photographs. Such work required some refinement in the process. Blackett and Chadwick succeeded in making the process automatic with photographs taken every 10 to 15 seconds; only at a speed like that could twenty-three thousand photographs be taken in a reasonable period of time. It should be pointed out that the photographic process was so organized as to have two simultaneous photographs of the chamber made perpendicular to each other. In this way it was possible to have two projections of the paths of particles and to determine the mutual position of their paths in space.

The chamber was filled with nitrogen, which was selected as it has the greatest probability of nuclear disintegration.

Among the photographs taken by Blackett there were an appreciable number that ended in "forks." They were precisely what interested the investigator.

What does a "fork" signify? It shows that from a certain point we no longer have one track but two that belong to two different particles. Such forks are shown in the photographs given in Figs. XII and XIII (see Appendix). From a careful analysis of these forks, Blackett concluded that they indicate collision processes of alpha particles and nuclei that occur at the apex of the fork. As a result of collision, the alpha particle deviates from its original direction and transfers a substantial part of its energy to the nucleus with which it collided. The nucleus endowed with great energy from the impact with the alpha particle begins to move at a high speed and ionizes the molecules it encounters. Since the charge and the mass of the nucleus is usually greater than that of the alpha particle, the ionization produced by the nucleus is much greater. Therefore, the track of the nucleus is shorter and thicker than the tracks of alpha particles.

And so a fork consists of two tracks, one that of an alpha particle, the other that of a nucleus interacting with the

alpha particle. However, in examining the tracks left by alpha particles in a cloud chamber filled with nitrogen, Blackett noticed forks of a different type. These forks are shown in Figs. XIV and XV in the Appendix. When these photographs were viewed in a stereoscope, the picture of what had happened was clear. The thick track of the alpha particle (Fig. XIV) ends in a fork, that is, two tracks emanating from one point, long before the alpha particle reaches the end of its range. Neither of the tracks of the fork resemble the tracks of alpha particles. The much thinner one that ends in the wall of the chamber is doubtless that of a proton, and the other, the short one, which is much thicker than that of the alpha particle, must be attributed to the nucleus itself. Where is the track of the alpha particle? There isn't any. The alpha particle got stuck in the nitrogen nucleus.

Nitrogen Converted into Oxygen

From among all the twenty-three thousand photographs, Blackett found eight forks indicating the disintegration of nitrogen nuclei. In all the eight acts of nuclear disintegration recorded in this way, the track of the alpha particle ends at the point of formation of the fork, that is, in all these cases the alpha particle that penetrates the nitrogen nucleus remains there. Not a single case was registered when an alpha particle causing nuclear disintegration of nitrogen rebounded from the nucleus and continued on its way even in a different direction.

The result of these observations gives grounds for concluding that what Rutherford observed was not, properly speaking, the disintegration of a nucleus. Rather it was a transmutation of the nucleus due to an alpha particle entering the nucleus of hydrogen, because herein is formed a new, heavier, and consequently, more complex nucleus with a larger atomic number.

Indeed, the mass of the nitrogen nucleus is 14, the atomic number, and hence the nuclear charge is 7. How does this nucleus change when struck by an alpha particle? The mass number of an alpha particle is four units, the charge—two. Therefore the system being formed will now have a mass

number of 18 and a charge of 9 units. This, however, would be the case if a proton had not been ejected from the nucleus. Due to the loss of a proton the mass number of the system diminishes by unity, as does also the charge.

To summarize, the nitrogen nucleus resulting from the capture of an alpha particle and the loss of one proton converts into a new nucleus of charge 8 units and mass number 17. The charge of 8 corresponds to an atomic number of 8. But the eighth place in the Periodic Table is occupied by oxygen. Thus, as a result of an alpha particle entering a nucleus of nitrogen there is formed the isotope "oxygen-seventeen" with simultaneous ejection of a proton. What we have described here in words may be written in the form of a formula similar to those used in writing chemical reactions. To do this, we must agree to how we shall designate the different nuclei.

Let us agree to denote the nuclei by the chemical symbol of the respective element with two numbers. One, the superscript, denotes the integral value of the atomic weight—the mass number, and the other, the subscript, the atomic number. Thus, for example, ${}_3Li^6$ denotes a nucleus of a lithium isotope of mass number 6. Using this notation, the transformation of a nitrogen nucleus is written as follows:

$$ {}_7N^{14} + {}_2He^4 \longrightarrow {}_8O^{17} + {}_1H^1. $$

Here N, He, O, H are the chemical symbols of the elements of nitrogen, helium (alpha particles), oxygen and hydrogen (proton). By analogy with chemical transformations, nuclear transformations are often called nuclear reactions. The above equation is therefore a nuclear reaction of "nitrogen-fourteen" with "helium-four." In this reaction, nitrogen converts into oxygen.

Blackett could prove by another method the validity of the conclusion concerning the transformation of nitrogen into oxygen. Since the photographs were stereoscopic, the angles formed by the trajectories of particles participating in the transmutations could be measured. Knowing these angles and also the initial speed of the alpha particle and the speed of the proton, one could calculate the mass of the newly formed nucleus by applying the laws of the conservation of energy and momentum. According to Blackett's measure-

energy of 7.7 million electron-volts, protons are ejected with a range of 90 cm., which corresponds to a kinetic energy of 10.7 million electron-volts.

The transformation of aluminium (if an alpha particle is captured by its nucleus) should proceed according to the following scheme

$$_{13}Al^{27}+_{2}He^{4}\longrightarrow {}_{14}Si^{30}+{}_{1}H^{1},$$

that is, from an aluminium-27 nucleus there is formed a nucleus of an isotope of silicon of mass number 30. The energy balance of the transformation of the aluminium nucleus can again be verified from the values of the masses. As in the preceding case, we have

$$m_{Al_{27}}c^2+m_\alpha c^2+W_\alpha=m_{Si_{30}}c^2+m_p c^2+W_p+W_{Si_{30}}$$

Thus

$$\frac{W_\alpha-(W_p+W_{Si_{30}})}{c^2}=(A_{Si_{30}}+A_H)-(A_{Al_{27}}+A_{He}).$$

The table of atomic weights of isotopes gives

$$\left.\begin{aligned}A_{Si_{30}}&=29.98290\\A_H&=1.00813\end{aligned}\right\}\ 30{,}99103,$$

$$\left.\begin{aligned}A_{Al_{27}}&=26.99069\\A_{He}&=4.00386\end{aligned}\right\}\ 30.99455$$

that is, the sum of the atomic weights of aluminium and the alpha particle is greater by 3.52×10^{-3} units of atomic weight than the sum of the atomic weights of silicon and hydrogen. But 3.52×10^{-3} units of atomic weight is the equivalent of 3.3 million electron-volts. By measuring the ranges of the proton and the silicon nucleus it is possible to determine their energy. It was found that $W_\alpha-(W_p+W_{Si})$ equals three million electron-volts. If account is taken of the errors in measuring the kinetic energy of the particles, as well as the errors in determining the mass of silicon and aluminium (the mass of aluminium is determined with an accuracy that does not exceed four units of the fourth decimal point, which corresponds to an energy of 400,000 electron-volts), it will be evident that the difference in both numbers lies within the limits of precision of mass measurements.

The conclusion to be drawn from this reasoning is exceedingly important. *When aluminium is converted into silicon, energy is released, and a very considerable quantity of energy—seven hundred thousand times greater than that obtained in the burning of an equivalent amount of carbon.*

This tremendous gain in energy naturally brings up the question of its practical utilization. It is not difficult, however, to see that there is no profit to be had in getting energy this way. Recall that one conversion of a nucleus of aluminium takes place per 125,000 alpha particles. The energy of each alpha particle is 7.7 million electron-volts. In order to gain an energy of three million electron-volts (the transformation of one nucleus of aluminium) we must expend $7.7 \times 125 \times 10^3$ million electron-volts uselessly. This is clearly not profitable.

Rutherford's discovery of nuclear transformations had not yet placed at the disposal of man the possibilities of using atomic energy. But these experiments, nevertheless, were the forerunners. They indicated the fundamental possibility of artificial liberation of energy from "the nuclear storehouse," and from that time on scientists never gave up this hope.

Why Don't All Elements Disintegrate Under the Action of Alpha Particles?

We have already noted that in Rutherford's first experiments, when the method of observation made it possible to note only fast protons with a range greater than the range of the bombarding alpha particles, only the nuclear disintegration of nitrogen, boron, fluorine, sodium, aluminium and phosphorus could be observed. However, when the observation technique was changed so that lower-energy protons could be watched, a number of other nuclei—neon, magnesium, silicon, sulphur, chlorine, argon and potassium—were found to disintegrate. We have already given the reasons why elements heavier than potassium do not split; the forces of repulsion between alpha particles and nuclei with a big charge are such that the alpha particle cannot come close enough to the nucleus if its kinetic energy is insufficient

for it to do the work required in overcoming the repulsive forces.

But Rutherford was unable to split not only heavy nuclei but even the very light ones like helium, carbon and oxygen. Why were they so stable? Maybe because these nuclei are in general indestructible and are simple structures, or maybe they are the same type of complex structures as other nuclei only more strongly bound together? It is not difficult to decide which of these assumptions is correct for since we know the mass of these nuclei we are therefore able to determine the binding energy, which, as we have shown, is the measure of stability of nuclei. However, we are able to determine the energy required for a nucleus that has captured an alpha particle to eject a proton, without resorting to this calculation.

By way of illustration, let us examine the transformation of helium. What should form from this transformation is easily seen in the following scheme:

$$_2\mathrm{He}^4 + _2\mathrm{He}^4 \longrightarrow _3\mathrm{Li}^7 + _1\mathrm{H}^1.$$

In line with this scheme, the energy balance should be written thus:

$$2m_{\mathrm{He}}c^2 + W_\alpha = (m_{\mathrm{Li}_7} + m_{\mathrm{H}})\,c^2 + W_{\mathrm{Li}_7} + W_{\mathrm{H}}.$$

In Table V we find the atomic weights and, hence, also the masses of the atoms in question:

$$A_{\mathrm{He}} = 4.00386,$$
$$A_{\mathrm{Li}_7} = 7.01816,$$
$$A_{\mathrm{H}} = 1.00813.$$

The mass difference $(m_{\mathrm{H}} + m_{\mathrm{Li}_7}) - 2m_{\mathrm{He}} = 0.01857$; the energy equivalent to this mass difference is 17.5 million electron-volts. Hence, the sum of the kinetic energies of the proton and the newly formed lithium nucleus must be less than the kinetic energy of the alpha particle by just this value. But the alpha particles used in Rutherford's experiments had energies of only 7.7 million electron-volts. It is clear that such an alpha particle could not have knocked out a proton even if it had penetrated into the helium nucleus. The alpha particles haven't sufficient energy to accomplish the above transformation scheme of helium into

lithium. If Rutherford had had at his disposal alpha particles with kinetic energies greater than 17.5 million electron-volts, he would probably have succeeded in splitting the helium nucleus and also the nuclei of carbon and oxygen, because the latter require for their nuclear disintegration an energy less than that for the transformation of a helium nucleus. But Rutherford did not possess such high-energy alpha particles and his experiments with these elements were a failure.

So much for Rutherford's experiments in the disintegration of atomic nuclei. The principal results obtained in these experiments may be formulated as follows:

1. It is shown that atomic nuclei are complex structures. They are capable of capturing alpha particles (helium nuclei). A proton (hydrogen nucleus) may be knocked out of them.

2. The artificial transmutation of elements is possible. Blackett proved, for example, that nitrogen nuclei bombarded by alpha particles are transformed into oxygen nuclei. However, this transformation is possible only due to the action of sufficiently fast particles. The energy required for this reaction comes to several million electron-volts.

3. Certain nuclear transformations are accompanied by release of energy, i. e., the kinetic energy of the nuclei resulting from the transformation is greater than the energy of the alpha particle that brought about this transformation.

4. The nuclei of the elements are not all of equal stability. Some nuclei are so stable that they do not undergo disintegration even by the energetic alpha particles which Rutherford used. Not several millions of electron-volts, but ten and even twenty million electron-volts are required for this transformation.

The Discovery of the Neutron

The decade that followed Rutherford's experiments in nuclear disintegration was relatively quiet. Laboratories were engaged in the study of the atomic nucleus. The nuclei of different substances were bombarded with alpha particles. Various details in the processes of nuclear transformations, the scattering of alpha particles, etc., were the subject of investigation and study. But this research did not focus

But a nucleus of charge 6 is the nucleus of an atom of an element which occupies the sixth place in the Periodic Table. It is carbon. Thus we come to the conclusion that in the capture of an alpha particle by a beryllium nucleus there is formed a nucleus of an isotope of carbon of mass 13.

However, it may be expected that the newly formed nucleus of carbon-13 will differ from the nucleus of a normal isotope of carbon-13, for a normal nucleus of carbon-13 has a very *definite* energy, while the nucleus (of carbon-13) formed from bombardment of beryllium will have an energy that depends on the kinetic energy of the alpha particle. This is what determines the difference between the normal carbon nucleus and the newly formed nucleus of carbon-13. The carbon-13 nucleus produced from beryllium and an alpha particle has excess energy. The question is: where does this energy go to?

If in the fusion of a beryllium nucleus and an alpha particle, a proton were ejected, as was the case in the earlier discussed nuclear transformations, then this excess energy could be carried out of the nucleus in the form of the kinetic energy of the proton. But since the experiments of Rutherford and Chadwick firmly established the fact that in the irradiation of beryllium by alpha particles no protons are produced, this way out for the excess energy is closed. There seemed to scientists only one possibility, that of energy release in the form of gamma rays.

This interpretation of the experimental results of Bothe and Becker ascribed great significance to these experiments because they meant the discovery not only of the presence of gamma radiation in nuclear transformations, but also a new type of nuclear transformation, the capture of an alpha particle without release of a proton. It was quite natural, therefore, that many workers became interested in the Bothe-Becker experiments and undertook a detailed study of beryllium radiation.

Making use of the fact that the penetrating power of gamma rays is a measure of their energy, scientists made careful measurements of the penetrating power of the beryllium radiation and, assuming that it was the gamma rays, they determined the magnitude of a quantum of these rays. It came out seven million electron-volts. Using these data, it was possible

to check the hypothesis of the beryllium radiation through the energy balance method just as we did in verifying the transformations which are accompanied by the ejection of protons. However, at this time the mass of a beryllium nucleus was not known precisely, and such control was therefore out of the question. Soon, however, new facts were illicited that made the Bothe-Becker hypothesis concerning the nature of the beryllium radiation highly doubtful.

The French scientists Frédéric Joliot and Irène Curie repeated the Bothe-Becker experiments with a modified technique of observing beryllium radiation. They replaced the Geiger-Müller counter with another instrument, an ionization chamber, that measured the ionization produced by beryllium radiation. As might have been expected from Bothe's assumption, the ionizing power of the beryllium radiation was insignificant. But when Joliot and Curie placed paraffin in the ionization chamber, they noticed a big increase in the ionization current (it nearly doubled). By introducing different substances into the chamber they found that a current increase takes place when substances containing hydrogen are inserted into the chamber to undergo beryllium radiation.

Joliot and Curie gave this fact the following interpretation. Quanta of gamma radiation possess a high energy. Therefore, they should also have a considerable momentum. When a gamma quantum collides with hydrogen atoms it transfers to the atoms a part of its momentum (just as a sphere can upon impact impart to another one its momentum). As a result, the protons begin to move, and since their ionizing power is very great in comparison with that of gamma quanta, even a small number of protons created by the beryllium radiation is capable of producing in the chamber the same ionization as that produced by the beryllium radiation itself. Since the mass of a quantum is small, by the laws of mechanics, the energy imparted to them during collision with nuclei will be the less, the greater the mass of the nucleus encountered by the quantum. This explains why precisely hydrogen in the ionization chamber produces such a strong action, whereas, for example, nitrogen with a mass fourteen times greater produces an effect fourteen times less than hydrogen.

That protons are produced by irradiation of hydrogen-containing substances with beryllium radiation was confirmed also by direct experiments, by observation in a cloud chamber. Such a chamber containing hydrogen (in the vapours of water and alcohol) and irradiated with beryllium radiation exhibited the appearance of proton tracks. It was even possible to measure their range, which was found to be 25 cm. From the range one could determine the energy of the protons and, with the latter, compute also the energy which the gamma-ray quanta should possess in order to impart their energy to protons upon impact.

The results of the calculation were unexpected. Joliot's figures showed that gamma rays should have an energy of 55 million electron-volts, something stupendous even by nuclear standards.

It was not only the results of the Curie-Joliot experiments, which were at variance with careful measurements performed earlier, that were unexpected, the very figure—55 million electron-volts—was unthinkable. Where could this enormous energy come from? All the more so since the bombarding alpha particle had an energy of only five million electron-volts. It seemed impossible to think of a simple explanation for the result obtained by Joliot and Curie. But still stranger were the results of investigations carried out by Chadwick. He subjected nitrogen and argon to the beryllium radiation. In both gases he detected particles having a large kinetic energy, which, it is true, was less than in hydrogen. Thus in nitrogen there originated particles with a range of only 3 mm. However, if we calculate what energy a gamma-ray quantum should possess so as to be able to transfer to nitrogen nuclei upon collision an energy that would permit them to traverse 3 mm. in the gas, it turns out that even 55 million electron-volts is not sufficient. To do this, a gamma-ray quantum would have to have an energy of 90 million electron-volts. Calculations for argon give a still bigger figure. To explain the experimental results, one had to attribute to the gamma quanta an energy of 150 million electron-volts!

To summarize, the assumption that the penetrating radiation produced during the bombardment of beryllium by alpha

particles is gamma rays, leads to contradictory results with respect to the energy of these rays.

1. From absorption experiments in lead we obtain seven million electron-volts.

2. From measurements of the ranges of recoil nuclei in hydrogen, the result is 55 million electron-volts.

3. From measurements of the ranges of recoil nuclei in nitrogen it is 90 million electron-volts, and from such measurements in argon the result is 150 million electron-volts.

These results that refer to one and the same magnitude are so different that doubt began to crop up as to the correctness of the principal assumption of Bothe and Becker. To resolve these doubts and eliminate the contradictions in the results obtained, only one thing could be done, and that was to change the existing conceptions concerning the nature of the beryllium radiation. This was exactly what Chadwick did.

He supposed that the radiation observed during irradiation of beryllium (and lithium and boron too) by alpha particles does not consist of gamma rays but is a beam of new and thus far unknown particles. These particles have dimensions close to those of atomic nuclei, and a mass roughly equal to that of a proton. However, in contradistinction to protons the new particles have no charge. The absence of charge suggested to Chadwick the name of "neutron."

An assemblage of such particles behaved in a very curious fashion. Since their charge is zero, an element consisting of such particles should occupy a place ahead of hydrogen in the Periodic Table. That would be a "zero element" which would be the prototype of the noble gases. Atoms of the zero elements would chemically be absolutely inert since they would not have any extra-nuclear electrons.

It would be no easy job to detect the existence of a "zero element." Since the atoms of a zero element consist only of neutral nuclei they do not interact with electric fields. Interaction between the "zero element" and the electrons and nuclei of ordinary elements would occur only in the case of very close approach. There would no longer be any "impenetrability" of atoms due to the mutual repulsion of their orbital electrons. To neutrons a substance appears not as some-

thing continuous, but in the form of a sieve with very large holes through which the neutrons can easily pass. If collected into a vessel, the zero element would in time leave it by going through its walls.

The only action of the zero element which makes it possible to be detected is a direct collision of neutrons and the nuclei of ordinary elements. The properties of the zero element are unusual indeed. We may note, however, that as early as 1920 Rutherford spoke of the possibility of the existence of a zero element, but the search for it at that time ended in failure.

The new hypothesis advanced by Chadwick made it possible simply and without contradictions to explain all the peculiarities of the "beryllium radiation," and the further development of nuclear research brought forward more and more evidence in confirmation of the correctness of this hypothesis: at present we consider the existence of neutrons just as real as that of protons and electrons.

Ways of Observing Neutrons

How is it possible to register neutrons, to observe their appearance, to distinguish them from other particles, and to study their properties?

All the diverse procedures employed in nuclear physics to observe and register individual particles are based on the action that these particles produce on the atoms of the medium in which they move. Tracks in a cloud chamber may be observed because alpha particles, protons and electrons possessing big energies, ionize the atoms they encounter. And water vapour condenses on the ions formed. Gamma rays are not directly observed in a cloud chamber because they hardly at all ionize the atoms they meet. From time to time they knock fast electrons out of the atoms. Thus a cloud chamber enables us to study gamma rays only by secondary characteristics, the appearance of fast electrons.

The Geiger counter also responds only when electric charges are created within it. The photographic method of particle registration is also possible only through continual ionization and the excitation of atoms of silver found in

the light-sensitive emulsion of photographic plates. But neutrons do not ionize the atoms they encounter.

Then how can we register them and distinguish their action from the actions of other particles? The characteristic feature which distinguishes neutrons from the other rays of nuclear physics is based on the property of neutrons to pass through considerable thicknesses of matter, such as lead. In this way, a beam of neutrons may immediately be separated from X-rays, and alpha and beta rays by filtering them through lead, that is, by passing the beam through a lead plate. But gamma rays are also able to pass through a plate of lead. How is one to differentiate between neutrons and gamma rays? One way is to utilize the difference between the two types of rays in their mechanism of interaction with matter.

Suppose a beam of gamma rays passes through a cloud chamber. What will we see in the photographs? Since gamma-ray quanta have a small mass, it is natural for one in colliding with a nucleus to transfer to the latter a very small part of its energy, so that such collisions will hardly be of any practical importance. Quite different is the collision of a gamma quantum with an electron. Since the mass of the electron is comparable to that of the gamma quantum, the latter can, upon colliding with an electron, impart to the latter an appreciable part of its energy. The result of the impact is a fast electron.

In a word, then, fast electrons and slow-moving nuclei form the picture of action of gamma rays. For this reason, the photographs of a cloud chamber pierced by gamma rays exhibit only the thin tracks of electrons. The movement of nuclei will not be visible at all due to their small energy.

Now what is the action produced by neutrons? Since the mass of a neutron is of the same order as that of light nuclei, the neutron is able upon collision to communicate to the light nuclei the greater part of its energy. Of special importance are collisions with hydrogen nuclei.

In view of the equality of masses, a neutron can, in a head-on collision, transfer to the proton all its energy. Billiard players will recall such collisions of two balls, when in a direct hit the first ball is stopped and the struck ball, which before was stationary, shoots off with the same speed as that of the incident ball.

The collision of a neutron with an electron is different. Due to its large mass the neutron, in a collision with an electron, imparts to the latter only a small portion of its energy (one two-thousandth part, on the average). Consequently, such collisions will produce low-energy electrons which go unnoticed in a cloud chamber. The number of such electrons will be small since a neutron does not act on the electric field of an electron. For this reason the ionizing power of a neutron will be small. Thus fast nuclei and slow electrons are the result of the interaction of neutrons and atoms. This picture is the reverse of what we had in the case of gamma rays. When neutrons shoot through a cloud chamber, the tracks of fast recoil nuclei should appear (protons, nitrogen nuclei). And since the latter ionize copiously the result should be a dense fog of thick tracks. It is the appearance of these tracks in the chamber that serves as reliable evidence of the presence of neutrons in the radiation under study.

To illustrate the action of neutrons, we give at the end of the book photographs (Figs. XVI and XVII) obtained by Joliot and Curie with a cloud chamber. Fig. XVI shows the tracks of a proton knocked out of paraffin by neutrons. The neutron source in this experiment was situated under and outside the chamber. Fig. XVII shows the track of a helium nucleus hit by a neutron.

The cloud-chamber method and certain other methods of registering neutrons not described here but based on the property of neutrons to form fast recoil nuclei were used during the early stages of the study of neutron properties. Subsequently, other, simpler and more convenient methods were found.

Nuclear Transformations That Produce Neutrons

It is hard to overestimate the significance of the discovery of the neutron. It may be stated authoritatively that all the subsequent successes of nuclear physics are determined to a great extent by this discovery. Scientists saw immediately that the new particles discovered by Chadwick should play a big role in nuclear processes and transformations.

Their very origin is the result of a nuclear transformation.

Let us write down the transformation scheme that produced the neutron. The beryllium nucleus has a mass number of nine and a charge of four units; after the capture of an alpha particle the mass number of the nucleus becomes thirteen, and the charge six. That would be the result if a neutron were ejected. After the ejection of a neutron the charge of the residual nucleus does not change, but the mass number is reduced by unity, becoming twelve. But the nuclear charge (six) means that we have obtained an element with the atomic number of six. This element is carbon. And so a nucleus of beryllium that emits a neutron through alpha-particle bombardment is converted into a nucleus of carbon-twelve. In writing the scheme of this nuclear transformation let us agree to designate the neutron by the symbol n; in the nuclear reaction schemes the superscript denotes the mass number and the subscript the charge, which is zero. In this notation the transformation scheme may be written as:

$$_4Be^9 + _2He^4 \longrightarrow _6C^{12} + _0n^1.$$

A similar transformation scheme may be written for boron and lithium, which also eject a neutron under bombardment by alpha particles. But here the reaction is more complex. Since beryllium consists only of one isotope one knows exactly what type of nucleus is being transformed in the production of neutrons, but lithium and boron have two isotopes each. This made it very difficult to determine what the transformation was, and at first mistakes were made. The main line of reasoning at first was that known isotopes should be produced in the nuclear transformation. On this viewpoint, one should attribute to the isotope of lithium-seven the emission of neutrons under bombardment by alpha particles. The end-product of the transformation will then be the isotope boron-10. If the transformation took place with a nucleus of lithium-6 the end-product would be an isotope of boron of mass number — 9. But since no such boron isotope was discovered, it was thought that the reaction should be written thus:

$$_3Li^7 + _2He^4 \longrightarrow _5B^{10} + _0n^1.$$

Similar reasoning suggested that the isotope boron-11 emitted neutrons, since the assumption that boron-10 should emit them led, it would seem, to an absurdity, namely,

$$_5B^{10} + _2He^4 \longrightarrow _0n^1 + X.$$

The X should be an element with atomic number seven (nitrogen) and of mass thirteen, but the existence of such an isotope of nitrogen was unknown. So Chadwick decided that the transformation scheme of boron under alpha bombardment should be

$$_5B^{11} + _2He^4 \longrightarrow _7N^{14} + _0n^1.$$

Great importance was attached to the establishment of this scheme of transformation because of the three elements (lithium, beryllium and boron) which when bombarded produced neutrons, the mass of boron was most exactly known and therefore, by establishing the character of the transformation and determining the kinetic energy of the neutrons produced, one might compute the mass of the neutron from the energy balance. And that is exactly what Chadwick did. The value of the neutron mass 1.0067 turned out slightly less than the mass of a proton (1.00758). However, it was subsequently found that the transformation of boron was incorrectly deciphered and the neutron mass value obtained by Chadwick was not correct.

Later, as our knowledge of nuclear transformations that involved neutrons developed and as the mass values of atoms were determined with greater and greater accuracy, a very precise measurement of the mass of the neutron was made. The neutron mass was found to be $m_n = 1.00893$ atomic units.

Thus the neutron proved to be just slightly heavier than the proton. The significance of this fact will be seen shortly.

Nuclear Transformations Produced by Neutrons

Can neutrons cause nuclear transformations? This question is in place, for earlier one could not assert that neutrons are capable of causing nuclear transformations. And if they are could such transformations be observed? We already know that nuclear transformations are exceedingly rare. Nearly a

million alpha particles are required to produce one nuclear transformation. But experimenters did not have at their disposal such quantities of neutrons. And it was difficult to determine exactly the number of neutrons produced. With sufficient approximation, one might say that when beryllium is irradiated with alpha rays from polonium, one neutron is produced per (roughly) hundred thousand alpha articles. Since experimenters had at their disposal sources emitting 10^9 alpha particles per second, the number of neutrons an experimenter could get was only about 10,000 per second. Could one, with so small a number of neutrons, set out in the difficult search of nuclear transformations? Wasn't this like fighting windmills? It might be that if Rutherford had had at his disposal sources of alpha particles of such small intensity, he wouldn't have discovered nuclear disintegration.

But with neutrons the situation is different. To see more clearly the difference between neutrons and alpha particles let us answer the following questions: Why are nuclear transformations caused by alpha particles so rare? Why is only one alpha particle in a million capable of doing this?

Recall that an alpha particle must have considerable energy in order to penetrate into an atomic nucleus and bring about a nuclear transformation. But alpha particles moving in a substance interact not only with nuclei but also with the atomic electrons. In its passage through the electron shells of an atom an alpha particle always loses a certain part of its energy. Of course, this part is not great. But the probability that an alpha particle in passing through an atom will pass close to the nucleus is also small. An alpha particle has to traverse many atoms before such a lucky event takes place, and in this way it loses in ionization either all its energy or so much that it won't have enough left to penetrate to the nucleus. Such is the inglorious fate of hundreds of thousands of alpha particles. And only those that hit a nucleus after passing through a small number of atoms are capable of producing a nuclear transformation.

Neutrons act differently. They have no charge and so in passing through an atom they hardly at all interact with the orbital electrons. That is why they don't lose energy. A neutron passes freely through hundreds and thousands of

atoms before encountering a nucleus. It is of no importance whether it hits an atomic nucleus sooner or later. Each neutron will undoubtedly (sooner or later) encounter an atomic nucleus and will be able to penetrate it, because the nuclear charge does not affect it. Therefore, if neutrons are competent to produce nuclear transformations they should operate very effectively. And though the number of neutrons is small, expressible maybe only in thousands, nevertheless the transformations they produce will be observable.

The first investigations were carried out with cloud chambers filled with different gases. In studying the photographs obtained, investigators discovered in some of them not single tracks of recoil nuclei but double and at times triple forks that indicated nuclear transformations. Fig. XVIII in the Appendix shows such a photograph. An explanation of it is given in the accompanying caption. Using such photographs it was possible to show that neutrons cause transformations in nitrogen, oxygen, carbon and neon. Their transformation schemes are as follows:

$$
\begin{aligned}
&{}_{7}N^{14} + {}_{0}n^{1} \longrightarrow {}_{5}B^{11} + {}_{2}He^{4},\\
&{}_{7}N^{14} + {}_{0}n^{1} \longrightarrow {}_{6}C^{13} + {}_{1}D^{2},\\
&{}_{8}O^{16} + {}_{0}n^{1} \longrightarrow {}_{6}C^{13} + {}_{2}He^{4},\\
&{}_{6}C^{12} + {}_{0}n^{1} \longrightarrow {}_{4}Be^{9} + {}_{2}He^{4},\\
&{}_{10}Ne^{20} + {}_{0}n^{1} \longrightarrow {}_{8}O^{17} + {}_{2}He^{4}.
\end{aligned}
$$

Of special interest is the reaction with carbon. Recall that neutrons arise from beryllium as a result of a transformation that follows the scheme:

$$
{}_{4}Be^{9} + {}_{2}He^{4} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1}.
$$

The transformation of carbon follows a reverse scheme:

$$
{}_{6}C^{12} + {}_{0}n^{1} \longrightarrow {}_{4}Be^{9} + {}_{2}He^{4}.
$$

This case is consequently the reverse transformation. If we call nuclear transformations reactions (and this is frequently done in analogy with chemistry) we have a case of a reversible reaction:

$$
{}_{4}Be^{9} + {}_{2}He^{4} \rightleftarrows {}_{6}C^{12} + {}_{0}n^{1}.
$$

It will become clear later on that reversible reactions are not a special case peculiar to beryllium. This property is common to all nuclear transformations. It is interesting to note that a transformation of an oxygen nucleus has also been observed (Rutherford was unable to bring about the transformation of oxygen by the very fastest alpha particles at his disposal).

Cases of the fission of atomic nuclei by neutrons were found in many photographs. The supposition concerning the effectiveness of neutrons and the ease with which they penetrate atomic nuclei was confirmed. Soon, however, Fermi performed experiments that demonstrated with extreme clarity the outstanding role of neutrons in the transformations of atomic nuclei.

Before discussing these experiments we shall have to digress and relate about other remarkable discoveries that were made in the same year, 1932.

Chapter V

THE DISCOVERY OF THE POSITRON

What Is a Positron?

In the year 1932, the *Science* journal carried a brief note by Anderson, in which he reported the discovery of a new particle in cosmic radiation. This particle has the same mass as the electron but in contrast to the latter it is not negative, but positive, just as the proton.

This discovery was just as unexpected as that of the neutron made shortly before.

A new particle appeared whose properties (mass and charge) were those of an elementary particle, one of the "building stones of the universe," as it were. Such particles are often called "elementary particles," and we shall hereinafter call them by this name. However, it should not be forgotten that this term is relative because what we call an "elementary particle" may in actuality prove to be a complex structure. It is only at our present state of knowledge, when we know nothing of their structure, that we can consider them "elementary."

Prior to 1932 we knew of two elementary particles, the proton, whose mass was taken as unity (or, to be precise, 1.00758), and the electron with its mass 1,836 times smaller than that of the proton. The charge of both elementary particles is equal in magnitude and opposite in sign. The electron is the bearer of negative charge, the proton, of positive charge.

True, it was not altogether clear where the alpha particles belong. Should they be considered elementary particles or a complex formation consisting of four protons and two electrons? On the one hand, the outstanding part played by alpha particles in the phenomenon of radioactivity and in

nuclear transformations speaks in favour, it would seem, of these particles being called elementary particles. On the other hand, considering that the mass and charge of alpha particles are multiples of the mass and charge of other elementary particles, one might suppose that they are complex structures built up of elementary particles.

Then a new elementary particle — the neutron — appeared on the stage of physics. It had unit mass but was devoid of any electrical charge. The number of "building stones of the universe" became three.

And now the news was that there existed still another type of elementary particle. It is worthy of note that Anderson's item appeared not in a scientific journal but in a popular-science magazine. Apparently, he himself thought that the data accumulated was insufficient to speak boldly of a discovery. Only after the work of Blackett and Occhialini, which fully confirmed the correctness of Anderson's observations, was it clear that the new discovery was a fact. In scientific circles (and even outside them) opinions were loudly voiced that new elementary particles thus far unobserved in terrestrial conditions had been discovered in cosmic radiation.

What then are these cosmic rays and how did development in this domain of knowledge lead to the discovery of the positive electron?

Cosmic Rays

Anyone who has ever studied radioactivity knows that a charged electrometer or electroscope discharges under the action of radioactive radiation. The reason is quite clear. Radioactive radiation produces in the air ions (electric charges of both signs) which reduce the charge of the electrometer or electroscope. For example, if the leaves of an electroscope are charged with positive electricity they will attract the negative ions which deliver up to the leaves their negative charge, thus gradually neutralizing the positive charge of the electroscope. The more ions there are formed in the air, the faster the electroscope discharges. It was pointed out earlier that this property was used as a basis for intensity measurements of radioactive rays.

Observations, however, showed that the leaves of a charged electroscope fall even in the absence of radioactive substance, though very slowly. The electroscope seemed to discharge "of itself." This spontaneous discharging was given what would appear at first sight a natural explanation. The opinion was expressed that minute quantities of radioactive substances were found scattered throughout the earth. The gamma radiation of these substances, which is capable of propagating very considerable distances, is the cause of such ionization of the air, which, though small, is found everywhere on the surface of the earth (or water) and which is the reason for the "spontaneous" discharge of all charged bodies. However, in 1910, it was discovered that the rate of discharge of an electrometer increases with the distance from the earth's surface. On the above assumption, one should expect that as the distance from the earth's surface increased the gamma radiation intensity would fall and with it also the rate of discharge of the electrometer. But experiments showed that this was not the case. The intensity of ionization increased perceptibly with altitude.

In studying this problem the German physicist Hess made some ten ascents in a balloon to altitudes up to 5 km. According to his data, the increase in ionization is noticeable from 400 metres on up.

Working from these experiments, Hess put forth the hypothesis that rays capable of ionization fall on our planet from outer space. These rays are partially absorbed by the atmosphere surrounding our earth and for this reason reach the surface of the earth appreciably attenuated. In ascending to higher altitudes we pass into regions where their intensity becomes greater. This is the reason for increasing intensity of ionization and the more rapid discharge of the electrometer.

As was subsequently brought to light, these rays do not originate at any one point in cosmic space. They come to the earth from all points, both facing the sun and from the opposite side. And they are present equally by day and by night.

Hess called them cosmic rays. Many workers became interested in the nature of these rays, and in the years that followed many investigations were devoted to them. All of this research consisted essentially in the study of the absorp-

tion of cosmic rays, but investigations proceeded in several directions. On the one hand, a study was made of the intensity variation of cosmic radiation (the variation of ionization intensity) with altitude. To do this, attempts were made to raise the measuring instruments to the greatest possible heights. On the other hand, absorption of cosmic rays was studied at the earth's surface. The measuring instruments were lowered into lakes and seas to the greatest possible depths. And finally, an investigation was made of the intensity variation of cosmic radiation (as a measure of it, we take the intensity of ionization produced by cosmic radiation) in traversing various substances (iron, lead, etc.).

Among the researches of the variation of intensity of cosmic radiation with altitude, mention should be made of the experiments with sounding balloons. A sounding balloon is a balloon equipped with an instrument that records automatically and at definite intervals the ionization of the air, the time, temperature and air pressure at a given instant. The three last figures taken together made possible a determination of the altitude at which the measurement of the ionization of the air was made.

The apparatus was made as light as possible (it weighed only 1.5 kg.) in order to reach the highest possible altitudes. In 1932 a sounding balloon reached a height of 27 km. and in 1933, 35 km. The results of these measurements are shown in Fig. 17 where the intensity of cosmic radiation is a function of altitude.

The measuring technique with sounding balloons was essentially improved by S. N. Vernov. He equipped the balloons with radio that communicated to earth the signals from instruments registering the cosmic radiation. This made it possible to determine the instrument readings directly during the ascent of the balloon and precluded many failures due to loss of balloons.

Whereas at the surface of the earth, the joint action of cosmic and radioactive radiations produces each second in one cubic centimetre of air an average of one ion pair, at an altitude of 2 km. 5.6 ion pairs are formed. The number of ion pairs produced increases rapidly with altitude. Beginning at 15 km., however, the rate of increase in ionization slows down, and at 22 km. ionization reaches a maximum

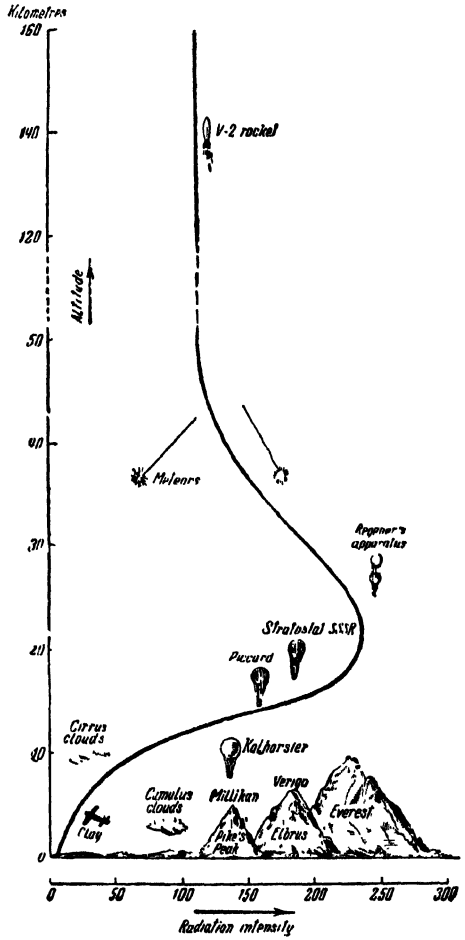


Fig. 17. The intensity of cosmic radiation as a function of altitude. The figure shows how and by whom the different altitudes were reached at which the cosmic-ray intensity was measured.

value of 240 ion pairs per cubic centimetre per second. Greater altitudes show a reduction in the ionization current. At 35 km. the ionization current corresponds to the formation in one cubic centimetre of only 175 ion pairs per second.

Intensity measurements of cosmic radiation with sounding balloons were conducted only to 35 km. For greater heights, rockets have been used. In 1948, V-2 rockets were used to measure the intensity of cosmic radiation at heights reaching to 160 km. The measurement was made with a Geiger counter. The number of pulses in the counter varied from 1.3 to 50 as the rocket rose from sea level to 20 km. As the ascent continued to 50 km., the number of pulses fell to 22 and did not change any more with altitude.

Summarizing, then, the intensity of cosmic radiation has a maximum at approximately 22 km. above sea level, but at an altitude greater than 50 km., the intensity of the rays is constant. The significance of this exceedingly important fact will be explained below.

The intensity of cosmic radiation was also measured at considerable depths under water. The first of such measurements were made by the Soviet physicist L. V. Mysovsky. Later, self-recording automatic instruments were lowered to depths of as much as 1,000 metres. As the depth increased, the intensity fell. But even at 1,000 metres under water cosmic radiation was detected, though the intensity was extremely small. Thus cosmic rays are capable of passing not only through the atmosphere of the earth but also through layers of water several hundreds of metres in thickness.

A comparison of data concerning the absorption of cosmic rays in water, iron, and in lead showed that all substances absorb cosmic rays in the same way, as long as the thicknesses of the absorbing layers are such that the weight of a column of the substance traversed by the rays is the same. This means that a one-metre layer of water of weight 100 gr./cm.^{2} absorbs cosmic rays in the same way that a layer of iron 12.8 cm. thick or a layer of lead 8.7 cm. thick does. These layers also have a weight of 100 grams per square centimetre. The absorption of cosmic rays by our atmosphere is equivalent to the absorption of a water column 10.3 m. in length.

The absorption coefficient of cosmic rays is very small. A 20-cm. layer of lead reduces their intensity by only one half.

Like X-rays and gamma rays, cosmic rays are capable of passing through considerable thicknesses of metal, the only difference being that the penetrating power of cosmic rays is greater than that of the hardest gamma rays.

For a long time scientists considered cosmic rays to be of the same nature as gamma rays, that is, they believed them to be the same electromagnetic vibrations as are light rays or X-rays. It was well known that the penetrating power of X-rays and gamma rays depends on their energy. The greater the energy of these rays, the less they are absorbed. Since the cosmic rays are absorbed considerably less than gamma rays it might be concluded that their energy exceeds the energy of all known gamma rays. From the absorption coefficient it was found that if cosmic rays are similar in make-up to gamma rays, then the energy of a quantum of cosmic radiation should be roughly equal to 30,000,000 electron-volts, which is just as much as should be released in the creation of a helium nucleus out of four protons and two electrons. Hence, Millikan assumed that cosmic rays are the result of the formation of helium nuclei in outer space, whence these rays come to the earth.

Millikan's viewpoint was very popular until Bothe and Kolhörster found that it was at variance with the facts. In their experiments they used a Geiger-Müller counter to register the cosmic rays in place of an ionization chamber connected with an electrometer. A Geiger-Müller counter, as we already know, registers each individual charged particle that passes through it. In place of one counter they used two (Z_1 and Z_2) arranged one above the other a certain distance apart (Fig. 18). Filters A of different substances could be inserted between the counters. The shielding made of lead and iron was to protect the counter from the action of radioactive radiation from surrounding objects. In this way it was possible to measure accurately the coefficient of absorption of cosmic rays in a substance A. The readings of both counters were automatically registered on a single tape by a self-recording instrument. The readings of one counter were recorded on the upper half of the tape and, those of the other counter on the lower half. An examination of the tape readings of the two counters showed that in a very large number of cases they coincided. The counters recorded simul-

taneously, as it were, the appearance of a cosmic particle. This was strange, for if cosmic rays are the same quanta as X-rays, the action of which is manifested by their creating electrons of considerable energy (and note also that each quantum can produce only one electron), then it is clear that the secondary charged particles (fast electrons) could not appear simultaneously in both counters. The simultaneous action of the counters could only be the result of one

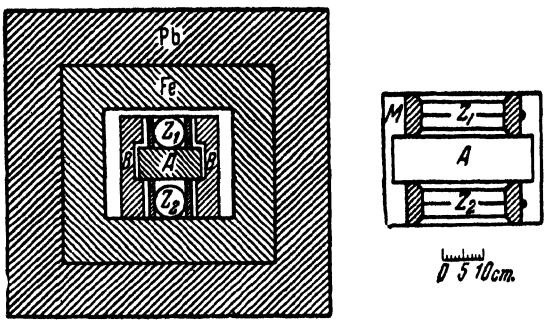


Fig. 18. Layout of the Bothe-Kolhörster experiments. Z_1 and Z_2 are Geiger-Müller counters; *A* is a 4.1-cm. thick gold filter; *B* and *M* are lead filters for protection against scattered radiation.

and the same charged particle (electron) passing through both counters and producing ionization along its path, that is, in both counters. Therefore the Bothe-Kolhörster experiments could be explained in only one way: the charged particles recorded by the counters are not secondary electrons arising from the action of cosmic quanta in the walls of the counter, cosmic radiation itself contains charged particles that possess tremendous energy which is sufficient to send them through both counters and also through a gold filter 4.1 cm. in thickness interposed between the counters. The attenuation factor of the particles producing ionization in both counters proved equal to the absorption factor of cosmic rays measured earlier by an ionization chamber. This fact was of great importance. It might be thought that the ionizing particles registered in the apparatus are present in the

cosmic radiation only in certain quantities. However, the fact that the measured absorption coefficients of the ionizing particles coincided with the absorption coefficient of the entire cosmic radiation compelled Bothe and Kolhörster to consider all cosmic radiation as consisting of charged ionizing particles. If we assume that all these particles are electrons, then their energy should exceed 100,000,000 electron-volts.

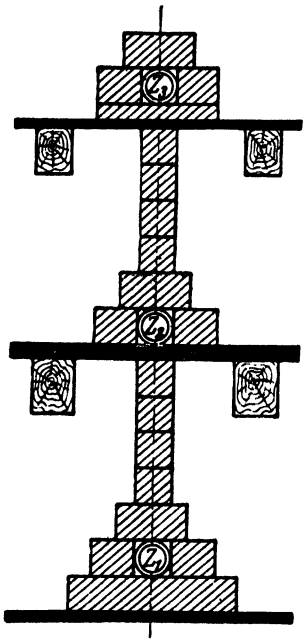


Fig. 19. Layout of the Rossi experiments. Z_1, Z_2 and Z_3 are Geiger-Müller counters arranged in a straight line. The crosshatched area is lead, the black rectangles, iron.

The Bothe-Kolhörster experiments were repeated by Rossi. He used a new technique that subsequently found wide application in cosmic-ray research. The essential idea behind his method was the use, for registration of cosmic rays, of three Geiger-Müller counters arranged in a straight line and connected to a rather complex amplifying circuit. In this circuit, a pulse produced in the counter, when the latter was traversed by a charged particle, was amplified to a definite magnitude. Pulses from all three counters were transmitted to a single amplifying valve, which carried a big current only when the pulses from all three counters arrived at the same instant. The relay of a mechanical numerator responded when a big current passed through this valve. Thus, a circuit of this type recorded only cases of simultaneous responses of all three counters. It is obvious that this could happen only when one and the same ionizing particle passed through all three counters. The counter circuit proposed by Rossi became known as a "coincidence circuit."

Rossi used lead as the filter (absorber) of cosmic rays. During the experiments the thickness of the lead layer was

varied and reached one metre. The arrangement of counters and lead filters used in Rossi's experiments is shown in Fig. 19. This layout was used to measure the number of particles passing through all three counters as a function of the thickness of the lead filter. Rossi's measurements confirmed the fact that cosmic rays at the earth's surface are a stream of ionizing particles that produce a discharge in the several counters through which they pass. At the same time, the Rossi experiments enabled new and extremely important conclusions to be drawn. It turned out that cosmic radiation is not homogeneous and consists of at least two parts, one of which is characterized by a large absorption coefficient. These rays are absorbed by a relatively small thickness of matter (5 to 10 cm. of lead). They were called the "soft" component of cosmic radiation. The other part of cosmic rays not absorbed by 10 cm. of lead is called the "hard" component. If the particles that make up this portion of the cosmic rays were electrons, their energy, as the estimations of scientists show, should exceed one thousand million electron-volts.

Skobeltsyn's Experiments

The assumption made by Bothe and Kolhörster was very soon confirmed by direct experiments carried out by the Soviet scientist D. V. Skobeltsyn. While making a study of the interaction of gamma rays and extra-nuclear electrons, Skobeltsyn placed a cloud chamber in a relatively strong magnetic field so as to determine the energy of the electrons being produced. His idea was this.

In a magnetic field, electrons do not move in straight lines but in circles, the radii of which depend on the kinetic energy of the electrons. Hence, the trajectories of electrons produced by gamma rays will be circles in a cloud chamber set in a magnetic field. And the radii of these circles will serve as a measure of the energy of the electrons. The greater the electron energy, the greater will be the radius of the circle.

The technique proposed and developed by Skobeltsyn was a great improvement over the tools that were in use for

the study both of nuclear processes and, in particular, of cosmic rays. Observing, in a cloud chamber placed in a magnetic field, the paths of electrons produced by gamma rays, he saw that they were usually in the form of arcs of radii of different curvature. The source of gamma rays was placed near the chamber.

Skobeltsyn measured accurately the radii of the curvature of trajectories, determined the electron energies and was able to draw several important conclusions relating to the mechanism of the interaction of gamma rays and atomic electrons, as well as the energies of the electrons.

However, of greatest interest in Skobeltsyn's work were the electron tracks which he found in cloud-chamber photographs. They were not at all curved. From the nature of the track, and the ionization produced by the moving particle it was quite obvious that it was an electron. The only trouble was that this electron did not want to curve, despite the strong magnetic field. Skobeltsyn drew the correct conclusion immediately. He concluded that these rectilinear tracks are also arcs of circles, the radii of which, however, are so great that the segments within the chamber do not exhibit the slightest curvature. His calculations showed that the energy of electrons moving in such circles would have to be not less than a thousand million (10^9) electron-volts. There could be no doubt that such electrons are in no way related to the gamma rays of radioactive substances used in his experiments. Skobeltsyn convinced himself of this directly. He removed the radioactive source and began to take photographs of the "empty" cloud chamber set in a 1,500-oersted magnetic field.

As he expected, the photographs of the "empty" chamber did indeed exhibit the straight tracks of electrons whose paths the 1,500-oersted magnetic field could not bend. On 1,700 photographs Skobeltsyn registered nearly 200 such tracks. It was abundantly clear that these tracks in the cloud chamber belong to charged ionized particles of cosmic radiation shooting through the chamber. It is also remarkable that Skobeltsyn's photographs relatively frequently exhibited not single tracks but double and occasionally even triple tracks; once a quadruple track was detected. Since Skobeltsyn's cloud-chamber photographs were stereoscopic, it was clearly seen that these tracks do not in any way get into

one photograph by accident, and that all these doubles, triples and quadruples are related. If we follow these tracks back we find that they all intersect at one point situated ordinarily somewhere close by the chamber, most frequently close to objects that surround the chamber.

The impression created was that the tracks observed by Skobeltsyn are of "terrestrial" origin, that they are not "cosmic rays," but are created as a result of the interaction of some sort of cosmic particles with our terrestrial atmosphere. That is how the following question, which is so important for an understanding of the cosmic rays arose: Are the fast charged particles really cosmic particles or are they all of secondary origin? Maybe they are all simply electrons knocked out of atoms of matter by cosmic rays. This assumption was all the more justified since, as we already know, cosmic rays in passing through the earth's atmosphere are strongly absorbed. It might, for example, happen that cosmic rays proper coming in from outer space are in the final analysis indeed short electromagnetic waves of the gamma-ray type, while the charged particles are electrons of secondary origin, the same as Skobeltsyn observed when he placed a gamma-ray source in a cloud chamber. Only these secondary electrons have tremendous energies, thousands of times greater than the energy of electrons produced by gamma rays from a naturally radioactive substance. And this in its turn would mean that the energy of cosmic rays is thousands of times greater than the energy of ordinary gamma rays. The assumption that a considerable portion of the electrons observed in cosmic rays are of "terrestrial origin" finds its confirmation in the fact that at high altitudes (upwards of 22 km.) the ionization produced by cosmic rays (Fig. 17) is less than at low altitudes. This means that a fraction of the secondary ionizing particles do arise in the earth's atmosphere.

True, it might turn out that the cosmic rays themselves are also charged particles (maybe these same electrons of stupendous energy). When these particles pass through the earth's atmosphere, or interact with bodies on the surface of the earth, secondary electrons may arise. For this reason, among the tracks discovered by Skobeltsyn in his cloud chamber there might be some that belong to the cosmic particles themselves.

How could one determine whether the primary cosmic rays too were charged particles or not?

The answer was very simple. Repeat Skobeltsyn's experiments on a large scale, get the primary cosmic rays in a magnetic field before they enter the earth's atmosphere and check to see if they are deflected by this field. If they are, then they must be charged particles, and if the magnetic field does not deflect them, then the cosmic particles have no charge. But how is one going to create such a field? Fortunately, it is not necessary, for we already have one, the magnetic field of our earth, which is weak, it is true, with a strength expressible not in thousands of oersteds but only in a fraction of an oersted, but the action of this magnetic field extends over a vast reach of space, and we know very well that the degree of deflection in a magnetic field is determined by the product of the strength of the magnetic field and the length of the path traversed by the particle in this field. A weak field acting over a long distance is capable of changing the trajectory even more than a strong field acting over a short distance. The earth's field is not sufficient for charged particles of very high energy to experience a perceptible change in their motion over short distances. But it can prove amply sufficient to deflect strongly from their rectilinear paths particles prior to entry into the earth's atmosphere.

Scientists had long been interested in the movement of electrons in the earth's magnetic field during the aurora borealis. Calculations were made and even experiments performed that demonstrated the behaviour of electrons passing close by a magnetized ball. Both calculations and experiments gave the same result: under the influence of the magnetic field of a magnetized ball, charged particles bend their trajectories being attracted to its magnetic poles.

The action of the magnetic field of the earth on cosmic rays should be in every way analogous, if only they are indeed charged particles. The cosmic rays should then move towards the magnetic poles, resulting in greater intensity of cosmic radiation at the pole (the geographic pole is close to the magnetic pole) than at the equator. The problem now was to investigate the intensity of cosmic radiation at various points on the earth's surface in order to determine how this intensity varies with latitude.

In 1933, the work of numerous expeditions that studied the intensity of cosmic radiation at different geographic latitudes was summarized. The measurements showed that at the equator the intensity of cosmic radiation is noticeably less than at the higher latitudes. It was clear that the primary, as it were, truly cosmic particles are (at least in part) charged particles, and for this reason, some of the straight tracks detected by Skobeltsyn in cloud-chamber photographs could belong to cosmic particles themselves.

What kind of particles were they? What was their energy, mass and charge?

These questions could be answered only if we succeeded in deviating them in a magnetic field. But we have already seen that the 1,500-oersted field used by Skobeltsyn was not sufficient to deflect them. Magnetic fields of considerably greater strength were needed.

How the Positron Was Discovered

This problem was undertaken independently by Kunze and Anderson. They used huge coils to produce in a large space a magnetic field of 20,000-25,000 oersteds into which was set a Wilson cloud chamber.

This powerful field had its affect, and many of the electron tracks, which in Skobeltsyn's photographs appeared as straight lines, were noticeably curved in the chambers of Kunze and Anderson.

Utterly unexpected, however, was the fact that not all the particle trajectories were curved by the magnetic field in one and the same direction. Some of the particles were deviated in one direction and others in the opposite direction. A portion were deflected in the magnetic field just like electrons, that is, particles charged with negative electricity, while others were deflected as if they had a positive charge (see Appendix, Fig. XIX). Kunze, and also Anderson at first, considered one part of these particles to be electrons, while the other part was thought to be charged positively (apparently protons), though as to ionizing capabilities both the positively and negatively charged particles were singularly alike.

The energy of these particles could be calculated from the curvature of the trajectories. For different particles it was different. The greater portion of them had an energy of the order of a thousand million electron-volts, though some of the particles had energies even several times greater.

A very thorough study of the question of interpreting particle paths in cloud chambers was made by Anderson. It had always been considered that a particle moves downwards, but it could be that they also move upwards. If this happened then all our deductions concerning the sign of the charge would be incorrect since the curvature of a negatively charged particle in a magnetic field would be the same as that of a positively charged particle moving in the opposite direction. Therefore, strictly speaking, we are not able, competently, to say from the form of the track in a cloud chamber whether a given particle is charged positively or negatively. The sign of the charge of a particle may unambiguously be deduced only when we know also the direction in which the particle moved.

How can we determine the direction of motion of a cosmic particle whose track is visible in a cloud chamber?

Anderson found an ingenious solution to this problem. He put across the middle of a cloud chamber a thick (5 mm.) lead plate. If the particle passes through this plate (and we know that cosmic rays penetrate very big thicknesses of matter) its initial energy will be reduced; this will result in a shorter radius of the curved trajectory of the particle after traversing the plate. Thus by photographing the movement of a particle through a layer of lead and then comparing the curvature of the trajectory before its entry into the lead and after it emerges, we will be in a position to judge where the particle entered the lead plate and this will give us its direction of motion. The latter is what we need for a final decision as to the sign of the charge of the particle and also to determine reliably the presence or absence of positively charged particles in cosmic radiation.

Anderson took several pictures and found in them some tracks that did not deviate as ordinary electrons do. While studying one such photograph he noticed an astounding thing: the picture (see Appendix, Fig. XX) exhibited the track of a charged particle that had passed through a lead

plate. In the upper part of the chamber, above the plate, the trajectory of the particle is somewhat less curved than in the lower part. This meant that the particle moved with a greater speed in the upper part than in the lower, and that, therefore, the particle, whose track is given in Fig. XX, had moved downwards.

Knowing the direction of motion of the particle and the direction of the magnetic field, it is possible to determine the direction in which the particle is deflected by the magnetic field, and hence also the sign of its charge. The particle was found to be charged positively. Anderson at first thought that this was a proton. Since the curvature was considerable, it was possible to measure its radius. This value is very important because with a knowledge of the mass one can calculate from the curvature radius and the magnitude of the magnetic field the energy of the particle. The measurements led to the following conclusion: if this is the track of a proton, then its energy after traversal of the lead plate should be only about 300,000 electron-volts. This result promptly told Anderson that the particle in question could in no way be a proton.

First, protons of this energy have a range of no more than 5 mm., whereas the length of the track as measured in this photograph came to more than 50 mm. Second, the ionizing power of protons of this energy is extraordinarily great, and therefore the track should be thick, whereas in fact it didn't differ at all from the tracks of electrons. One could state straightaway that the ionizing power of this particle is the same as that of electrons.

Anderson correlated the ionizing power of the particle, the length of its trajectory, and the curvature of the radius, and concluded that the mass of this positively charged particle should be roughly equal to the mass of an electron and not a proton.

The particle whose track Anderson had observed in the cloud chamber was of electronic mass but was charged *positively*. This was a new species of particle theretofore unknown to science. It was called a positive electron, or "positron."

To conclude the analysis of the picture in Fig. XX, we need only say that the energy of the positron prior to entry into the lead plate was 63 million electron-volts, and after

emergence from it, only 23 million electron-volts; thus 40 million electron-volts were lost in passing through the lead plate.

Following this discovery, many workers took up the study of the properties of positrons.

The "Birth and Death" of Electrons

Positrons were first discovered by Anderson in cosmic radiation. Very soon, however, it was found that they can also arise in terrestrial conditions; they may, for example, be produced by gamma rays, requiring for the purpose relatively small energies — one million electron-volts. Besides it was noted that positrons play no small role in nuclear transformations, as witness the part played by them in the discovery of the so-called phenomenon of artificial radioactivity. We shall discuss this discovery in Chapter VII, for the present we describe the experiments that uncovered the remarkable properties of the new positron particles.

Since the discovery of X-rays, scientists were engaged in the study of their absorption in different media. The phenomenon of X-ray absorption found broad application in technology and medicine and was of great scientific importance. For this reason, it was necessary to make a thorough study of the laws governing this phenomenon. Numerous investigations established the mechanism of the absorption of X-rays. It was found that these rays are absorbed in atoms of matter. The energy of an X-ray quantum is transferred to one of the extra-nuclear electrons of the atom, most often to one in the *K*-shell, the quantum itself disappearing in the act.

Quantitative relationships were also established that determined the variation of X-ray absorption as a function of the energy of the quantum (the frequency of the rays) and of the material of the absorber. The absorption laws of X-rays were extended throughout the entire range of frequencies which were obtainable by the technical means then in use for generating such rays. Using quantum mechanical methods it was possible to calculate the absorption of X-rays: equations were obtained that were in good agreement with experiment-

al data and that enabled the new regularities to be extended to a greater frequency range, that is, to rays with higher quantum energies.

Since the nature of gamma radiation is identical with the nature of X-rays (the gamma rays differ from X-rays only in the energy of the quanta), it was natural to think that also the mechanism of their absorption by various substances would be the same as in the case of X-rays, and that the quantitative laws, such as the dependence of absorption on energy, would be expressed by one and the same equation both for gamma quanta and for the X-rays.

Investigations that were carried out confirmed this assumption generally. It came out that the absorption of gamma rays is governed by the same laws as is that of X-rays. However, this commonness of the absorption laws obtains only if the energy of a gamma-ray quantum does not exceed one million electron-volts. When the study of the absorption of gamma rays of greater energy was begun, it was found that in addition to the ordinary photoelectric absorption* for gamma rays of energy in excess of one million electron-volts, there existed yet another type of absorption. Gamma rays of these energies are more strongly absorbed than follows from the laws of photoelectric absorption.

It was established that this additional absorption increases with the energy of the gamma quantum. At a given energy of the quantum it was also the greater, the greater the atomic number of the absorbing material. For a long time no explanation could be found for this phenomenon, which was uncovered long before the discovery of the positron and which was known as anomalous absorption of gamma rays. It was only after the discovery of positrons that this manner of absorption of gamma rays was found to be inevitable.

The anomalous absorption of gamma rays turned out to be connected with the origin of positrons. To understand this fact, observations were made of the absorption of gamma rays in lead filters in cloud chambers. To do this, a lead plate was placed in a chamber and pictures were taken that regis-

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* The absorption of a quantum by one of the extra-nuclear elecrons is termed photoelectric absorption.

tered the particles which arise in this plate when it is irradiated with gamma rays. The cloud chamber was placed in a magnetic field to determine the charge of the particles produced. Many of the photographs exhibited the tracks of positrons. Fig. XXI (see Appendix) shows such a photograph with the track of a positron arising from the action of gamma rays in a lead plate. Some of the pictures exhibit the tracks of two particles originating at one point. These particles are always deflected by the magnetic field in different directions, and hence their charges are of different sign.

From the ionizing power of these particles one could conclude that they are of the same (electronic) mass; in other words, the observed particles were an electron and a positron.

Positrons are thus born by the action of gamma rays of energy above one million electron-volts. They always arise in the form of two particles or, in the parlance of physicists, in electron-positron "pairs." The fact that lead plates irradiated in a cloud chamber frequently give rise to only a single particle, a positron or an electron, is explained by the observation that the other particle deflected by the magnetic field in the opposite direction gets stuck inside the lead plate.

Investigations of cloud-chamber photographs taken during the passage of gamma rays through thin foils and through a gaseous medium confirmed the fact that the positron always arises as an integral part of an electron-positron pair. The formation of pairs by gamma rays in various gases in cloud chambers was studied in detail by a number of workers, including the Soviet physicists L. V. Groshev and I. M. Frank. One of the pictures obtained is shown in Fig. XXII in the Appendix.

The gamma-ray-produced pairs observed in cloud-chamber photographs enabled one more important conclusion to be drawn. Pairs are observed in cloud chambers in a magnetic field. But, as we know, charged particles in a magnetic field move in circles whose radii depend on the energy of the particles. Hence, their energy may be determined by the deflection of the pair of particles. Precise quantitative experiments were performed with gamma rays emitted by thorium C″. This radioactive preparation was selected because the energies of the quanta it emits were well known. The essential thing was that in the radiation of thorium C″ there is only

one sort of gamma rays capable of producing positrons. The energy of their quanta came to 2.6 million electron-volts.

Measurements of the track curvatures of the electron and positron showed that the total energy of both particles was in many cases equal to 1.6 million electron-volts. If we take into account that the self-energy due to the mass of the particle is approximately equal to 0.5 million electron-volts (both in the case of an electron and a positron) it will be clear that all the energy of the gamma quantum of thorium C″ passed to the electron and positron.

Thus the gamma quantum vanishes (is absorbed) in the formation of a pair. Its energy passes in part into the kinetic energy of the particles of the pair (1.6 million electron-volts) and partially (one million electron-volts) it goes to produce the pair itself. The amount of energy required to form a pair is determined from the mass of the particles of this pair. The process of pair production may be written as:

$$\left.\begin{array}{l}\text{gamma-ray quantum} \longrightarrow \text{electron} + \text{positron} \\ \gamma \longrightarrow e^- + e^+,\end{array}\right\} 9$$

where e^- is an electron, e^+ a positron, and γ a gamma-ray quantum.

Since the production of one pair requires the expenditure of one million electron-volts, it is understandable why the anomalous absorption of gamma rays begins to be observed only when the energy of the gamma-ray quantum rises above one million electron-volts.

Positrons are born not only through the action of gamma rays, but also due to high-energy electrons.

A careful study of the mechanism and the laws of positron formation was made by the Soviet scientist A. I. Alikhanov and his school. By ingenious and precise experiments they were able to show that the quantitative relations that determine the probability of positron production coincide, with a high degree of accuracy, with calculations based on quantum mechanics.

Theoretical conclusions predicted that in the process of the transformation of a gamma ray into a positron-electron pair a third body should participate. This part is usually played by the atomic nucleus, which does not change at all in the process but whose presence is necessary for the gamma

rays to produce the pair. Furthermore, the greater the charge of the nucleus, the more probable will be the transformation of the gamma quantum into an electron and positron. It is precisely for this reason that the anomalous absorption of gamma rays increases with the atomic number of the absorber.

Since positrons can be produced in terrestrial conditions, a natural question is: Why were they not observed before? The answer is that they have a small lifetime, existing only as long as they possess a big kinetic energy. A slow-moving or stopped positron interacts with the electrons of the substance in which it is slowed down and as a result the electron and positron *vanish*, but not without a trace: two gamma-ray quanta appear shooting out in opposite directions. Each of them has an energy of roughly 0.5 million electron-volts. This process may be written as follows:

$$\text{positron} + \text{electron} \longrightarrow 2 \text{ gamma quanta} \qquad (9a)$$

The discovery of the production and annihilation of pairs impressed the scientific world no less than did the discovery of radioactivity in its time. Just as prior to the discovery of radioactivity the atoms of matter were believed to be immutable and indivisible, and eternally existing, so also it was customary to regard charged particles (electrons) as permanently existing, never being created or destroyed. Electrons, the physicists thought, could only pass from one body to another, carrying their charge with them in the act. Sometimes the electrons could be found free, but in all cases and all phenomena and processes their number was considered constant. And now it appeared that this is not so: electrons can disappear; there can take place an annihilation of electrons (and also positrons, of course), accompanied by the appearance of gamma-ray quanta. Electrons could also arise at the expense of gamma quanta disappearing.

Thus, experiments in production and annihilation of positrons and electrons destroyed one more convention that had existed among naturalists, that of the immutability of electrons; and they provided brilliant confirmation of the principle of dialectical materialism concerning the mutual transformability of different forms of matter.

Chapter VI

THE ARTIFICIAL TRANSFORMATION OF ATOMIC NUCLEI

In Chapter IV we discussed in detail the experiments of Rutherford and his pupils dealing with the artificial transformation of atomic nuclei. However, the word "artificial" used to characterize these experiments calls for a certain explanation. Its use with respect to Rutherford's experiments was to emphasize the fact that the transmutation of nuclei was not spontaneous, but was to a certain degree the "work of the experimenter." And, indeed, in these experiments the artificial transformation of atomic nuclei was not wholly the work of the experimenter, for he had to use as projectiles alpha particles which themselves are the product of the natural decay of atomic nuclei. It was of course quite natural that experimenters wished to dispense with radioactivity and to produce a truly artificial transmutation which would make use not of the alpha particles from naturally radioactive substances, but of particles (helium nuclei, hydrogen nuclei) to which a big energy is artificially imparted in the laboratory.

Already from experiments with the transformation of atomic nuclei using alpha particles it was obvious that to produce nuclear transformations one needed particles with energies of several million electron-volts. This energy was necessary so that the alpha particle might overcome the repulsive forces and penetrate into the atomic nucleus. It was natural to expect that protons with a smaller charge and therefore experiencing less repulsion would be able with less energy to penetrate into the nucleus. Furthermore, it was demonstrated theoretically that particles of the most diverse energies, even of relatively small energies, could

get into the nucleus. However, the probability of penetration into the nucleus depends on the energy of the particle. The greater the energy, the better are its chances of entering a nucleus in a collision.

We shall not dwell here either on the involved calculations of the theory or on an analysis of the equations obtained. From them it follows with complete assurance that if the experimenters had at their disposal alpha particles of lower energies but in considerably greater quantities, we would then be able to observe the transformation of nuclei. The naturally radioactive substances provide a relatively small quantity of alpha particles per second, whereas protons can be had in much greater quantities. Recall here that a stream of protons equivalent (as to charge transfer) to a current of one milliampere, consists of 6×10^{15} particles per second. Further note that in their first experiments physicists had to do with sources emitting 10^{7}-10^{9} alpha particles per second. Thus, it becomes evident that it might be hoped to obtain the transformation of nuclei through the use of protons of relatively small energies. Calculations showed that an energy of the order of several hundred thousand electron-volts (500,000 to 600,000) would be amply sufficient.

The First Apparatus for the Artificial Disintegration of Atomic Nuclei

The first successful attempt to transform nuclei with fast protons was made by Cockcroft and Walton. To impart to the protons such big energies they applied the method of electric acceleration so often used in laboratories.

Acceleration of charges in an electric field is fully analogous to the acceleration of bodies in a gravitational field. When a stone falls it acquires energy that increases with the height from which it falls. So also with an electric charge. When the latter "falls" in an electric field it acquires energy that increases with the "electric height" (the potential difference) from which it "falls." As the charge moves in the electric field it gains kinetic energy equal to the product of the charge and the potential difference. Hence,

if we wish to impart to electrons or protons an energy of hundreds of thousands of electron-volts we must first of all create an electric field with a difference of potential of this magnitude. But this is not all. Into this electric field we must inject protons, that is, the positive ions of hydrogen atoms. And this is still not all. We must see that the protons introduced into the electric field can "fall" freely in it so that they can acquire kinetic energy.

Since alpha particles and protons moving in air make collisions with molecules and lose their energy, it is clear that it is impossible to create "artificial projectiles" if the protons are accelerated in an electric field in air. The molecules must be removed from the path of the protons; in other words, the electric field must be created not in air but in a vacuum. At that time, the solution of such a problem was no easy matter.

True, transformers for voltages of the order of several hundred thousand volts were already being manufactured. And there even existed some unique ones for one million volts. But they could not be used because a transformer supplies alternating voltage while what was needed was a constant electric field, direct voltage. There were ways of "rectifying the voltage," that is, of transforming alternating voltage into direct, but, to do this, one had to have a condenser of the required voltage and a rectifier capable of handling a double voltage, that is, one of the order of a million volts. This was the first difficulty, because at that time there were condensers and rectifiers (kenotrons) for voltages of only 200,000 volts.

The second, and possibly greatest, difficulty was the requirement of a high voltage in a vacuum.

Scientists were able to produce the required very high vacuum (a pressure of less than one hundred-millionth of an atmosphere). And they were also able to create an electric field in the vacuum, as witness the X-ray tube, which is an evacuated glass tube with two electrodes sealed into it, one at each end, and an electric field between the electrodes. This was all familiar. It was also known that the greater the electric field we wished to create, the longer must the tube be and the farther apart must the electrodes be that extend out of the tube. It would seem that all one needed

was a tube of sufficient length and the problem would be solved. But it was already known that extending the length of the tube is effective only to a certain limit, approximately to two hundred thousand volts. No increase in length could exceed this limit.

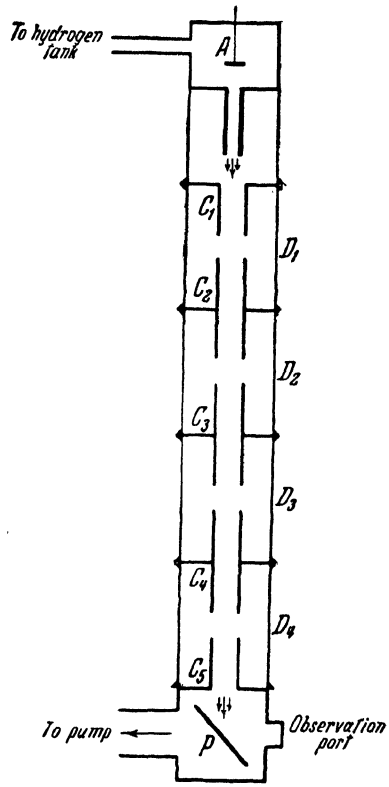


Fig. 20. Schematic diagram of the Cockcroft-Walton tube.

Cockcroft and Walton had to solve two problems: one was to create a constant electric field of 600,000-800,000 volts, the other to apply this voltage to the evacuated tube.

They reasoned that if it is impossible to apply to the tube a voltage greater than 200 kilovolts they wouldn't demand "the impossible." They decided to create between the electrodes a potential difference of only 200 kilovolts, but instead of taking one pair of electrodes, they took five pairs. If an electric field is created between the first and second electrodes with a potential difference of 200 kilovolts, and the same between the second and the third, the third and the fourth, and the fourth and the fifth, and then if all these electric fields are in one direction, there will be a difference of potential between the first and the fifth of 800,000 volts. This required but one condition: that the ions undergoing acceleration should be allowed to pass between the electrodes from one electric field into the other. This was a rather simple matter: it was sufficient to make relatively small openings in the centres of the electrodes for the passage of the

ions. Experience, however, showed that the tube operates more reliably if the form of the electrodes is slightly more complex. Fig. 20 gives schematic diagram of the Cockcroft-Walton tube. The letters C_1, C_2, C_3, C_4, and C_5 denote the electrodes. A potential difference of 200,000 electron-volts is established between each adjacent pair of electrodes. D_1, D_2, D_3 and D_4 are glass cylinders connecting each

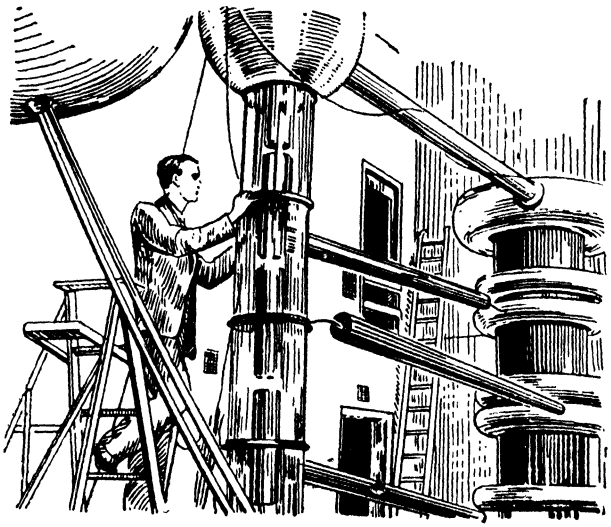


Fig. 21. Crane's tube built on the Cockcroft-Walton principle.

pair of electrodes A special sealing preparation was used at the junction points of the cylinders and electrodes to ensure a perfect vacuum, that is, so that no air should get into the tube at these points The upper electrode C_1 had an opening through which protons from the discharge apparatus A entered the tube The protons passed through the electrodes acquiring an energy equal (in electron-volts) to the difference of potential between the first and the last electrodes, and hit the target P with the substance under investigation. Fig. 21 shows a tube built by Crane according to the above principle.

Such was the solution of the second problem. Let us now see how the first problem, that of producing a constant potential, was solved. In attacking this problem, Cockcroft and Walton made use of earlier rectifying schemes and voltage multiplication. To get an idea of the principle behind their apparatus let us examine the diagram in Fig. 22.

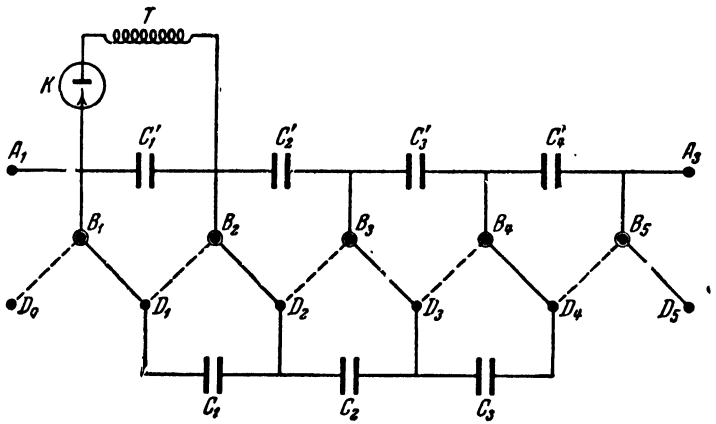


Fig. 22. The accelerating part of the Cockcroft-Walton apparatus.

Let us assume that we have a transformer T that gives a voltage of 200 kilovolts. Using a kenotron K, let us charge condenser C'_1 to this voltage. Let us connect in series with this condenser auxiliary condensers C'_2, C'_3, C'_4 and, in addition, let us set up a group of condensers C_1, C_2, C_3 connected in series, each one of which must be designed for a voltage of 200 kilovolts. The group of condensers C'_1, C'_2, C'_3, C'_4 can be connected with the group C_1, C_2, C_3 through a switch. All condensers had one and the same capacity and the switch had two positions. In the first position, terminal B_1 is connected with D_1, B_2 with D_2, B_3 with D_3, B_4 with D_4, B_5 with D_5; in the second position, B_1 is connected with D_0, B_2 with D_1, B_3 with D_2, B_4 with D_3, and B_5 with D_4. These positions of the switch are indicated in Fig. 22 by different lines; the first position is shown with a solid line, the second position with a dashed line.

What will happen when we flip on the switch? First (the first position) condenser C'_1 will be connected in parallel with condensers C_1 and both condensers will charge up to 200 kilovolts. When the switch is thrown to position two, condenser C'_1 will be disconnected, and condenser C_1 will be connected in parallel with condenser C'_2; C'_2 will then charge up to half the difference of the potential which was on condenser C_1, whereas condenser C_1 will discharge by one half. Just like condenser C'_2, it will now have a potential difference of 100 kilovolts. Now return the switch to the initial position. C_1 will again be connected with condenser C'_1 and will again charge up to 200 kilovolts. Simultaneously, condenser C_2, which in this position of the switch will be connected with condenser C'_2, will also charge up. Condenser C'_2 will discharge to 50 kilovolts, and condenser C_2 will charge to 50 kilovolts. Now return the switch to the second position. Condenser C_1 will again be connected with condenser C'_2. The voltage on them will become equal and will reach the average of what had been on both condensers. C_1 had 200 kilovolts, and C'_2 had 50 kilovolts, so each condenser will now have 125 kilovolts. But, aside from this, condenser C'_3 will partially charge up because it will be connected with condenser C_2. Condenser C'_3 will charge up to 25 kilovolts. Continuing this switching process we will see that gradually all the condensers C'_2, C'_3, C'_4 will become charged to 200 kilovolts, and the potential difference at the ends A_1, A_3 will reach 800 kilovolts, the required voltage. And what is more, the voltage is divided into parts of 200 kilovolts each, which is exceedingly important for operation of the tube, since it becomes possible to apply to each electrode the relatively small voltage permissible for its operation.

In the actual apparatus, the switching device was not mechanical. It was found possible to solve the problem by using a system of kenotrons that operate like a mechanical switch.

The Disintegration of Lithium

Let us now examine the investigations themselves. The first experiments were performed with lithium. Cockcroft and Walton were right in thinking that it would be easiest

for hydrogen nuclei (protons) to penetrate the lithium nucleus since due to its small charge (3 units) the repulsive forces between this nucleus and a proton would be less than between a lithium nucleus and an alpha particle.

The transformation of lithium nuclei was observed by the method of scintillations, which required that a screen with zinc sulphide be placed at a certain distance from the target and protected from direct proton hits.

Already in the first observations, it was found that when lithium was bombarded by protons of such comparatively small (by nuclear standards) energies as 500 to 800 thousand electron-volts, bright scintillations appear on the zinc sulphide screen. It was obvious that some sort of particles that produced scintillations were being ejected from the lithium. But what kind of particles were they? Maybe they were protons impinging on the lithium target and scattered by it.

To decide this question, Cockcroft and Walton interposed between the screen and the lithium target thin plates of mica. By varying the thickness of these plates and observing the number of scintillations one could note the plate thickness at which they ceased altogether. This made it possible to determine the range of the particles, and hence, also their energy. The range of particles causing scintillations proved to be very big, corresponding to 8.4 cm. of air. Such a large range was reliable proof that the particles observed by scintillations were not protons scattered by the target, because such protons have ranges that do not exceed 3 cm. Thus these particles are produced by lithium as a result of its bombardment by protons. Control experiments, in which the lithium target was replaced by a copper target confirmed this conclusion because in the latter case no particles of range 8.4 cm. were observed.

The artificial transmutation of elements became a fact. What kind of transmutation was this and what were the particles observed?

There was only one answer to this question. Since these particles produce scintillations and yet are not protons, then they are alpha particles, and, therefore, this proton-produced nuclear transformation should be written as:

$$_3Li^7 + _1H^1 \longrightarrow _2He^4 + _2He^4.$$

In words, this means that a lithium nucleus absorbed a proton and disintegrated into two alpha particles.

This conclusion could be checked experimentally since from the laws of mechanics it followed that if as a result of the penetration of a proton into a lithium nucleus, the latter is split into two alpha particles, these particles will fly apart with equal energy in opposite directions.

Now, are two alpha particles actually formed in the transformation of lithium and do they shoot out in different directions? An answer to this question was the aim of the work of Dee and Walton. They decided to connect a cloud chamber to the tube in which the transformation of lithium took place, and observe the ranges of particles produced in this transformation. It was no simple matter, of course, to connect the cloud chamber to the tube, since the latter required water vapour, whereas the tube, in which protons were accelerated, had a good vacuum. Without water vapour the chamber would not work, and with water vapour the tube wouldn't work. But a way out was found. The end of the tube (Fig. 23) that enclosed the target *B* was made in the form of a net covered with a foil of mica that was so thin that high-energy alpha particles could pass through it. The mica foil passed alpha particles but still served as a reliable barrier to air and water vapour. Thus one could have a good vacuum in the tube, the necessary elasticity of water vapour in the cloud chamber, and at the same time permit the alpha particles to pass from the tube into the

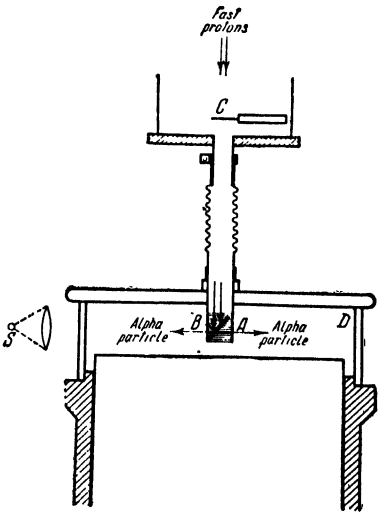


Fig. 23. Layout of the Dee and Walton experiments.
A — window; *B* — target bombarded by protons; *C* — shutter; *D* — cloud chamber; *S* — light source.

chamber. One of the photographs obtained is shown in Fig. XXIII (see Appendix). It gives a clear picture of pairs of tracks of alpha particles shooting out in opposite directions.

The energy of an alpha particle may be determined from its range; it was found to be 8.8 million electron-volts. Since there are two such particles, their total kinetic energy will come to 17.6 million electron-volts. This is an enormous energy. And this fact enables us to make a quantitative check of extraordinary significance.

An Experimental Verification of Einstein's Equation

The question at hand is the relation between mass and energy which was established by Einstein in the theory of relativity. As we pointed out above, in the relativity theory the relationship between mass m and energy E is expressed by the equation:

$$E=mc^2 \tag{8}$$

where E is the energy of the body, m its mass, and c the velocity of light.

Equation (8) is of extraordinary and fundamental significance. It establishes the relation between characteristics of matter (mass and energy) that had formerly seemed independent. It is also exceedingly important to nuclear physics since nearly the whole mass of a body is concentrated in its atomic nucleus. From this equation it follows, that the principal portion of the energy of atoms is locked up in the nuclei.

We have already had occasion to apply equation (8). We used it to explain the mass defect of various atomic nuclei when establishing the energy balance in nuclear transformation and tried to understand the possible nature of these transformations. However, up till the 1930' s this equation had not been verified by direct experimental measurements because only big changes in energy could enable one to measure the change in mass. The experiments in the transformation of lithium nuclei made it possible for the first time to carry out an experimental check of the correctness of equation (8).

In these experiments, a proton of energy 800,000 electron-volts impinging on a lithium nucleus produces two alpha particles, with an overall total kinetic energy of 17.6 million electron-volts. Since no other energy changes take place, the excess kinetic energy of the alpha particles (16.8 million electron-volts) could only be related to a reduction in the mass of the nuclei of lithium and hydrogen. In this transformation, the participating atoms are lithium-7, hydrogen and helium. The masses of all these atoms are very well known (See Table V, p. 99.). The mass of a hydrogen atom is 1.00813 units of atomic weight, the mass of an atom of lithium is 7.01816, and that of a helium atom, 4.00386.

Let us compare the masses of the particles prior to and after the nuclear reaction. The sum of the masses of the atoms of lithium and hydrogen is 8.02629, and the sum of the two atoms of helium is 8.00772 units of atomic weight. Hence, the sum of the masses of two helium atoms is 0.01857 units of atomic weight less than the sum of the masses of the atoms of lithium and hydrogen. But we already know that 1.07×10^{-3} unit of mass corresponds to an energy of one million electron-volts, and 0.01857 unit of mass will correspond to 17.35 million electron-volts.

To summarize, when two alpha particles are formed from a lithium nucleus and a proton there is a reduction of mass, and simultaneously of energy, that corresponds to 17.3 million electron-volts, and at the same time energy is released (in the form of the kinetic energy of alpha particles) to the extent of 16.8 million electron-volts. Both of these figures, of which one is computed from equation (8) and the other is measured with an accuracy within the limits of experimental error, coincide.

Thus the study of the disintegration of lithium nuclei by protons permitted an experimental check and confirmation of one of the most important equations in nuclear physics:

$$E = mc^2$$

Philosophers of the idealist school endeavoured to use this equation to prove that "mass is converted into energy," and that consequently the matter which they so hate is "dematerialized," it "vanishes." In actual fact, however, nothing of the sort takes place. The reasoning of these idealists

about "the transformation of mass into energy" does not find any confirmation in equation (8) and is the result of a purposeful distortion of the genuine scientific content of this equation.

Equation (8) shows that a definite quantity of any type of energy is always associated with a definite quantity of mass. For this reason, any increase or decrease of energy is accompanied by a decrease or increase in mass by a value determined by this equation. In each case, including the nuclear reaction ${}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4$ considered here, the laws of the conservation of mass and the conservation of energy are obeyed.

Energy is a characteristic of the motion of matter; mass is also a characteristic of matter. Thus, equation (8) is a brilliant confirmation of dialectical materialism, which states that there is no matter without motion, just as there is no motion without matter.

The Van de Graaff Generator

The success of the experiments of Cockcroft and Walton, who succeeded in transforming nuclei with artificially accelerated particles, and an awareness of the fact that the magnitude of the electric field places a limit on the possibilities that arise, made scientists seek other ways and methods of increasing the kinetic energy of particles.

One of the successful attempts to obtain a high potential was that of Van de Graaff. He succeeded in modernizing the well-known electrostatic machine and in using it to accelerate charged particles.

Take an insulated sphere and try to charge it as much as possible, that is, to as high a potential as possible.

In physics experiments at school a common demonstration is that of charging an insulated pith ball. To do this, another charged object (for example, a glass rod, rubbed on cat's fur) is brought into contact with the ball. Using this simple technique it is possible to charge the pith ball to a rather small degree. There are many factors that limit the attainment of a high potential — first of all because there is a small charge on the rod itself. Better results may be

achieved if the charge is transferred from the charged rod to the ball many times in succession (that is what is usually done in electrostatic machines). Each portion of electric charge brought in by the rod would increase the charge of the ball. But we would soon reach a certain limit.

One of the most important reasons for the limit of electrization of the ball is that in fact it is not fully insulated and during the interval between two communications of charge a part of it leaks away. And the leakage increases with the charge of the ball (with respect to surrounding objects). It is obvious that to achieve a better charge of the ball, we must supply greater and greater quantities of charge with greater frequency. The best thing is to supply it with electric charges continuously.

And on the other hand, attempts must be made to reduce the leakage of electric charges from the ball. Leakage losses are due to two causes: first, the charge leaks out through the insulation to which the ball is attached; second, the charge leaks off the ball into the air. With increase in potential, leakage increases both through the insulation and via the air.

It was long ago established that the amount of charge leakage through the air depends on the size of the ball and on the condition of its surface. The greater the radius, the less the leakage. Any irregularities on its surface, especially sharp projections, contribute appreciably to charge leakage.

With this knowledge, we can formulate the requirements for charging a ball to a high potential. First of all, the ball, or "conductor," as it is called, should be large in size, with a radius of several metres. It should be as smooth as possible, without irregularities and projections on its surface. And the attempt should be made to impart to it continuously as large a charge as possible. Of course, the ball should be as far as possible from surrounding objects. The best thing would be an empty room with smooth walls with the ball properly insulated. To meet these requirements was no easy task and Van de Graaff had to overcome many different complications.

Fig. 24 gives a diagram of a Van de Graaff electrostatic generator using a transformer T to create a potential of sev-

eral tens of thousands of volts; to a system of points O (our diagram shows only one point) is conveyed a potential of such a magnitude that intensive discharges begin from the points. A constant potential must be maintained on the point so that only charges of one sign are discharged. For this reason, a rectifier K (kenotron) is connected in the transformer circuit, and sometimes also a condenser C to equalize the potential.

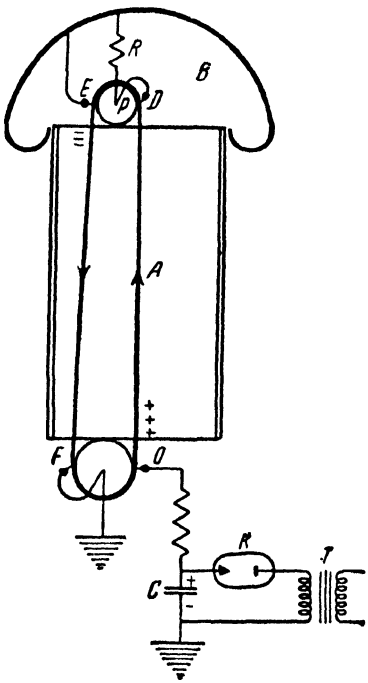


Fig. 24. Diagrammatic sketch of a Van de Graaff electrostatic generator.

A belt A of insulating material (rubberized material is best) is kept in constant motion past the points from which a charge is removed. The positive charge is transferred onto this belt and together they move towards the shell B. Inside shell B, which is a conductor, is a device D (also consisting of a system of points) that removes the charge from the belt.

Charge removal takes place as follows. When a charge located on the belt approaches point D, it induces a charge of opposite sign on the point (in this case, a negative charge). The positive charge arising on the point is transferred to the roller p connected with the point. The negative charge leaks off point D and destroys the positive charge on the belt, whereas the positive charge on the roller p passes through resistor R onto the outer surface of the conductor B. In this way, the flow of charges transferred by the belt passes to the conductor, charging it and creating a difference of potential between the conductor and surrounding objects (ground). The charge on the conductor may be increased if

the belt is made not only to transfer positive charges to the conductor but also to remove from it negative charges. For this purpose, a system of points E connected with the inside surface of the conductor B is arranged inside the shell opposite the roller p on the outgoing side of the belt. Since the current of positive charges going from roller p to conductor B passes through resistor R, there appears a voltage drop on this resistor which is the greater, the bigger the resistance R and the charge conveyed by the belt. Now, roller p is charged positively with respect to conductor B, and hence also with respect to point E. It is always possible to select the resistance R such that the potential difference between roller p and conductor B could bring about a discharge from point E. Since the potential of roller p is greater than the potential of conductor B, negative charges will leak off point E, whereas positive charges of the appropriate magnitude will pass over to the outer surface of the shell.

In a word, then, the belt introduces into the shell a positive charge and removes the negative charge, thus charging up the shell to a point where the charge leakage becomes equal to the charge coming to the shell. Where do the charges from the shell go? A part leaves the shell through the tube connected to conductor B; this is the "useful" current. The other part leaves through the resistors (for instance, through the insulation of the shell) and through the so-called corona. The corona current is essentially what determines the potential to which the shell is charged. The greater the curvature radius of the conductor, the greater the potential to which it can be charged.

The tube to a Van de Graaff generator is ordinarily of the type of the Cockcroft-Walton tube. Since it is necessary to supply this tube with a sectional potential, the usual procedure is to connect to the conductor B (parallel to the tube) a potentiometer, that is, a resistance divided into as many equal parts as there are sections in the tube. Given a direct current, there is an equal voltage drop on equal resistances, and therefore all the potential on the potentiometer is split up into several equal parts, each of which is connected to an individual section of the tube.

The necessity of making the conductor very large, and also of keeping it as far away as possible from surrounding objects

make electrostatic generators unwieldy and expensive structures. They usually require special buildings. By way of illustration we give several photographs of electrostatic generators. Fig. 25 shows one of the first electrostatic machines. This "little" generator has a conductor with a diameter

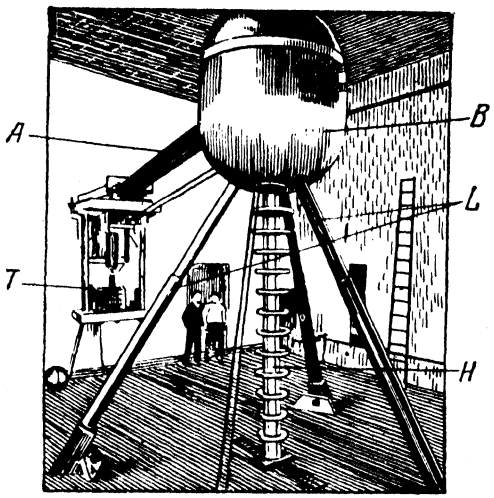


Fig. 25. Electrostatic generator with a conductor diameter of two metres.
A — charge-carrying belt; *B* — conductor; *T* — transformer for charging belt; *H* — tube; *L* — insulators.

of two metres. It is capable of accelerating particles to 1.5 million electron-volts.

Fig. 26 shows another electrostatic generator that consists of two conductors, one becomes charged positively, the other, negatively. Each of the shells has a diameter of about 4.5 metres. The difference of potential between the shells can reach five million volts.

The big drawback of electrostatic generators is their unwieldiness. But this deficiency can be overcome. It is possible to reduce leakage of charges from the conductor not by increasing its size, but by improving the insulating qualities of the medium surrounding the conductor.

It has long been known that compressed gases possess far greater electric strength than ordinary air. And so successful attempts were made to enclose electrostatic generators in special tanks in which the gas was under a pressure of several atmospheres (at present the pressure within generators reaches 16 atmospheres), and to fill them with a gas that possessed considerable electric strength.

Naturally, the tube, in which the charged particles are accelerated, also has to be placed in this tank.

A generator of this type is shown in photograph XXIV (see Appendix). This is a double photo. First the inside arrangement of the generator was photographed, and then (on the same plate) the generator as a whole. The accelerating tube in this generator, as also in the Cockcroft-Walton tube, is made of separate parts divided by metallic electrodes, to each of which is connected a part of the total voltage generated in the unit. The tube together with the insulating supports of the conductor is mounted inside the tank where the pressure of the gas is as much as 16 atmospheres.

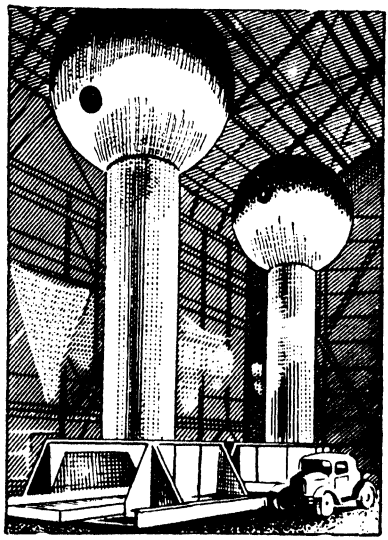


Fig. 26. An electrostatic generator capable of developing five million volts.

A few figures will give the reader some idea as to the size of this type of electrostatic generator. The generated potential is two million volts and the length of the tube 142 cm. The diameter of the metal tank reaches 135 cm. with a length of 305 cm. A generator of this kind easily fits into an ordinary room. At present, such generators are made to produce a potential of five million volts.

Electrostatic generators are now widespread. They make

it possible to impart to particles energies of the order of five million electron-volts with relatively strong currents through the tube. Their remarkable quality is ease and smoothness in voltage control (which is achieved, for example, by varying the charging current), and also stability of the voltage obtained.

Acceleration by an Alternating Electric Field

Electrostatic generators enabled scientists to accelerate charged particles to energies of five million electron-volts. But even such energies proved too low. It was necessary to increase the energies of the particles. To do this with high-voltage apparatus was impossible and so other ways of accelerating ions had to be found. Though it may seem strange at first glance, but alternating voltage was what was used for this purpose. Credit for this method of acceleration goes to Lauritsen and Sloane.

How can ions be accelerated by alternating voltage when a variable field periodically changes the direction of electric force acting on the particle? During one part of the time the particle will be accelerated (when the direction of the force coincides with the direction of motion), but during the other part (when the direction of the electric field changes and the force is directed against the movement of the particle) it will be decelerated. If a particle is first accelerated and then decelerated, and the deceleration continues the same length of time that the acceleration does, it is hard to expect that this motion will produce any considerable energy. It is precisely for this reason that physicists strove to accelerate charged particles through the use of a constant electric field.

But a way was found to obviate the difficulties involved in accelerating charged particles in an alternating electric field. Suppose that between electrodes A and B (Fig. 27) there has been created an alternating electric field. Let us place between these electrodes a number of tubes labelled C_1, C_2, C_3, C_4. These tubes play the part of electrodes, the only difference being that such electrodes are of a special type since there is no electric field inside the tubes. When

a difference of potential is applied to the tubes, *the electric field will be enclosed in the space between the tubes, whereas inside the tubes themselves there will be no field.* Since the electrodes are tubular in form, the particles being accelerated can pass through them freely.

A charged particle moving from A to B will experience the action of the field only in the space between the tubes, while inside the tubes they will move by inertia. By varying the length of the tubes, it is possible to vary the time

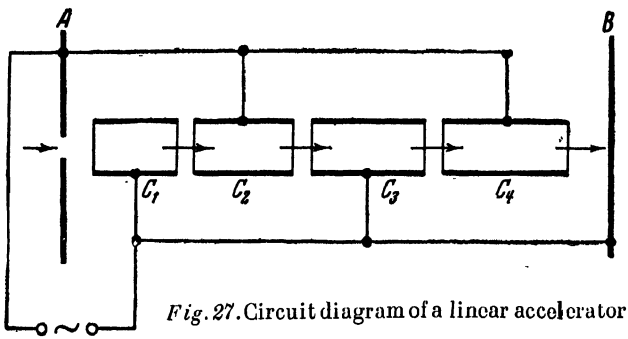


Fig. 27. Circuit diagram of a linear accelerator.

interval during which the particle is outside the action of the field. Let us connect the electrodes A and B and the tubes C_1, C_2, C_3, C_4 together so that electrode A and tubes C_2 and C_4 have one potential, and electrode B and tubes C_1 and C_3 will have the same potential but different signs.

Let us assume (to be concrete) that the potential of electrode A is greater than that of electrode B. Then a positively charged particle in moving from electrode A to tube C_1 will be accelerated by the electric field, but on the section from tube C_1 to tube C_2 (that is, in moving from a smaller potential to a greater potential) it will be decelerated. This will be repeated in its further motion (from C_2 to C_3 it will gain speed, and from C_3 to C_4 it will slow down), if a time-constant potential difference is applied to the system of tubes. The acceleration of particles will be different if to the electrodes A and B (and hence also to tubes C_1, C_2, C_3 and C_4) there is applied an alternating potential difference $V=V_0 \sin \omega t$.

Let us assume that a positively charged particle emerges from electrode A at the instant the electric field is directed from A to B (that is, the potential of electrode A is higher than the potential of electrode B) and has a maximum value. Under the action of the electric field it will move from A to B and gain in speed. When the particle reaches tube C_1 it will have acquired an energy equal to eV_0, where e is the charge of the particle, and V_0 is the maximum potential difference between A and C_1. When the particle passes inside the tube, the electric field will cease to act on it, and it will move at a constant speed. While it is in movement inside tube C_1 the electric field will change, the potential difference between A and C_1 will diminish to zero, and will then change its sign, that is, the potential at electrode C_1 will become greater than that at electrode A. Let us select the length of tube C_1 such that at the instant the potential difference between A and C_1 reaches its maximum negative value, the moving particle will have reached the end of tube C_1. Tube C_1 is followed by tube C_2 connected with electrode A so that the potentials of A and C_2 are equal at any instant of time.

Since at the instant being described, that is, when the moving particle has entered the space between the tubes, the potential of electrode B will be greater than the potential of electrode A, the particle will again gain speed over the path from C_1 to C_2 and will acquire additional energy equal to eV_0. Thus when a particle passes inside tube C_2 (where there is no electric field) it will have an additional energy $2eV_0$.

As the particle moves inside tube C_2, the electric field between the tubes and the electrodes will continue to change. The potential difference will again change its sign and the potential of electrodes C_2 and C_4 will again become greater than at electrode B and tube C_3.

Let us select a length of tube C_2 such that at the instant the potential difference between A and B reaches a maximum value, the particle will have reached the end of tube C_2. Since C_2 is followed by a new electrode C_3 that has the same potential as electrode B, the particle will again speed between C_2 and C_3, because at this instant the potential of electrode C_2 will be greater than the potential of electrode C_3. Having

passed tube C_2 the particle will have an energy equal to $2eV_0$. Between C_2 and C_3 it will again be accelerated, and so on. When the particle reaches electrode B, its energy will be equal to $5eV_0$, because over the path AB it will have been accelerated five times.

The remarkable thing is that the particle accumulates an energy $5eV_0$, *without having once passed through a difference of potential greater than* V_0.

This accumulation of energy was possible because every time the electric field changed from acceleration to deceleration, the particle was in a space devoid of an electric field. This was the essence of the Lauritsen-Sloane idea. If conditions were created such that the particle is outside the electric field when the latter is changing its direction, it is possible to impart to the particle being accelerated a large energy by means of a relatively small alternating voltage. It was found that it was not only possible but even more convenient to use an alternating electric field (instead of a constant one) to accelerate particles. And big electric fields were not needed. One had only to handle the movement of the particle with care and protect it from the action of the electric field at those instants when the field was directed unfavourably.

It is easy to figure out how the length of the tubes C_1, C_2 C_3, ... (inside which the particle moves) should change during the time the electric field changes from one maximum value to the other, oppositely directed, one. Since we demand the transit time of the particle inside each tube should be one and the same, namely equal to one half the period of voltage variation, the length of these tubes must increase just as the speed of the particle does. The speed of the particle varies as the square root of its energy, and the energy of the particle inside each successive tube increases by one and the same magnitude,

$$l_1 : l_2 : l_3 : l_4 : l_5 : \ldots = 1 : \sqrt{2} : \sqrt{3} : \sqrt{4} : \sqrt{5} : \ldots,$$

where l_1 is the length of the first tube, l_2, the length of the second, etc.

If the number of such tubular electrodes is n, then the

additional energy acquired by the particle during its travel from electrode A to electrode B will obviously be:

$$(n+1)eV_0.$$

Thus it appears possible to communicate large energies to particles through the use of a small potential difference V_0, if we take a system of a large number of electrodes of the proper length.

Lawrence tried this method and he succeeded in accelerating ions of mercury to an energy of 1,260,000 electron-volts by using a system of 31 electrodes, between which he applied a potential difference of 42,000 volts.

Mercury ions were selected as the particles to be accelerated so as to reduce the frequency of the alternating current. It must be recalled that to accelerate particles one must have high-frequency oscillating electric fields. At an energy of one million electron-volts mercury ions have a velocity of 10^8 cm./sec. It takes 10^{-7} sec. to cover a distance of 10 cm. Therefore, the ordinary 50-cycle voltage is no good for the acceleration of particles. The voltage frequency must be appreciably greater; not less than 20 millions of times per second must the voltage change so as to be able to accelerate ions of mercury. To accelerate protons one needs a field that varies as rapidly as 300 million times per second. The necessity for fields of high frequency and at the same time the huge size of the apparatus were factors that prevented the method suggested by Lauritsen and Sloane from becoming widespread. However, at the present time, in view of the progress achieved in vacuum techniques and electronics, these difficulties are being overcome and linear accelerators (this is the name given to machines operating on the principles of the Lauritsen-Sloane method) are being developed further.

The Cyclotron

The large number of electrodes was an essential drawback in the above-described method. Lawrence suggested using only two electrodes, but in a magnetic field.

A charged particle in a constant magnetic field will move in a circle. The radius of curvature of the circle R depends

on the mass of the moving particle, its speed and the magnitude of the magnetic field. This relation is given by the equation:

$$R = \frac{mu}{He}, \tag{9}$$

where R is the radius of curvature of the trajectory of the particle, m its mass, H the magnetic intensity, and e the charge of the moving particle. It may be seen from this equation that the radius of the circle described by the moving particle is directly proportional to its speed. If the speed of the particle varies, the radius of its trajectory will also vary, and (this is extremely essential) the radius will change exactly as many times as the velocity. We know that the length of the circumference is proportional to its radius. Consequently, the time during which a charged particle moving in a magnetic field sweeps out a circle will be the same, irrespective of the speed of the particle. This time is:

$$T = \frac{2\pi R}{u} = 2\pi \frac{m}{eH}. \tag{10}$$

Equation (10) shows that the time during which a particle moving in a magnetic field describes a circle depends only on the magnitude of the magnetic field and the ratio $\frac{e}{m}$. For particles of a given mass m and a charge e the period of revolution T will be constant if the value of H is constant.

Lawrence utilized the fact that the time of complete revolution is independent of the energy of the particle. He made the electrodes, between which there was created an oscillating electric field, in the form of a hollow cylindrical box cut into two halves (Fig. 28). There was no electric field inside each box (just as in the case of the cylindrical tube of the linear accelerator). The field exists only in the space between these electrodes, and is used to impart energy to the charged particles.

If two such electrodes are placed in a magnetic field and if its intensity is selected such that the time T becomes equal to the period of variation of the electric field, then a positively charged particle emerging from electrode B at the instant the difference of potential between B and A is

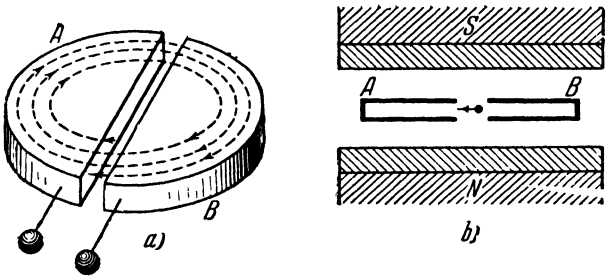


Fig. 28. A cyclotron.
a) accelerating chamber; b) its position between the poles of a magnet.

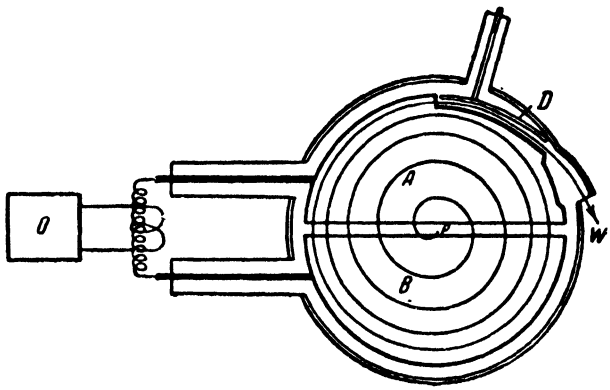


Fig. 29. Cyclotron chamber. An ion formed at point P moves in a spiral under the action of a magnetic field perpendicular to the plane of the drawing and experiences a successive series of accelerations in the gap between the halves A and B of the accclerating chamber; it is then deflected by means of a deflecting plate D and emerges through window W.

positive, will gain speed each time it passes from electrode to electrode.

Fig. 29 illustrates the trajectory of a moving particle. Let a particle emerge from point P at an instant when the potential of electrode A is greater than the potential of electrode B. In time $T/2$ the particle will have described a semicircle and will emerge from electrode B and will begin to move in the direction of electrode A, but during the time

$T/2$ the potential difference will have changed its sign. The potential B will become greater than A and the particle will again gain speed. Inside electrode A the particle will move with a greater velocity and during the time $T/2$ it will again describe half a circle (of a greater radius), following which it will again be accelerated in moving from A to B. Thus every time a particle passes from electrode toelectrode it will be accelerated. The radius of motion of the particle will increase with the acceleration. So, to impart to the particles higher energies it is necessary to make the electrodes larger. The region of the constant magnetic field must also be the bigger, the higher the energy of the particle. By taking a big enough chamber and magnet, it is possible to obtain particles of considerable energies.

The machine operating on this principle became known as the cyclotron. Just as in a linear accelerator, particles in the cyclotron are accelerated by using an oscillating electric field. The magnetic field is needed only to regulate the movement of the charged particle and enable it to pass the gap between the electrodes at the time when the electric field in it is favourably directed.

The cyclotron principle proved very fruitful; Lawrence soon obtained a beam of deuterons (a deuteron is the nucleus of deuterium, or heavy hydrogen, the hydrogen isotope of

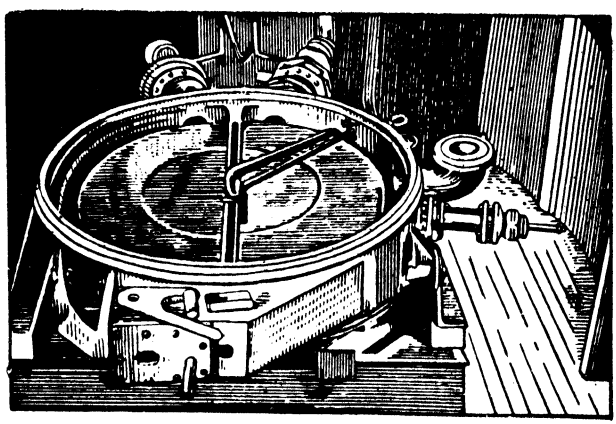


Fig. 30. The chamber of a cyclotron.

mass number 2) of energy three to five million and later 10 million electron-volts. Besides this, he succeeded in getting beams of protons and helium nuclei with energies of several million electron-volts.

As we have already pointed out, the magnitude of energy acquired by a particle in the cyclotron depends on the size of the machine. The greater the energy of the particle, the greater the radius of its trajectory in a magnetic field. In the case of a given radius, the energy of protons, deuterons and helium ions will differ. The greater the mass of the particle, the less will be its energy. Still more pronounced is the effect of the charge of the ion undergoing acceleration. The energy acquired by a particle in a cyclotron of given size is proportional to the square of the charge of this particle.

Fig. 30 shows the chamber of a cyclotron and Fig. 31 gives a general view of a cyclotron with pole pieces 1.5 metres in diameter. Fig. 32 illustrates the cyclotron in "action." The track of a beam of deuterons may be seen with an energy upwards of 15 million electron-volts. The track is visible because the air that has been ionized by the beam of deuterons luminesces. The distance traversed by deuterons of this energy in air is approximately two metres.

The Betatron

The cyclotron is one of the most ingenious of physical tools. To it goes credit for a good portion of the successes achieved by modern nuclear physics. It was precisely the cyclotron that put into the hands of scientists those "projectiles" which were so necessary for studying the properties of atomic nuclei. But this machine too had its imperfections.

To see why, let us turn again to equation (10) which determines the period of revolution of a charged particle in a magnetic field. As may be seen from this equation, the cycle of accelerated particles is a function not only of the magnitude of the magnetic field, but also of the mass of the moving particle. For a particle to gain energy from the oscillating electric field, it must pass through this field at definite intervals, to be more exact, when the direction of the electric field coincides with the direction of its movement, other-

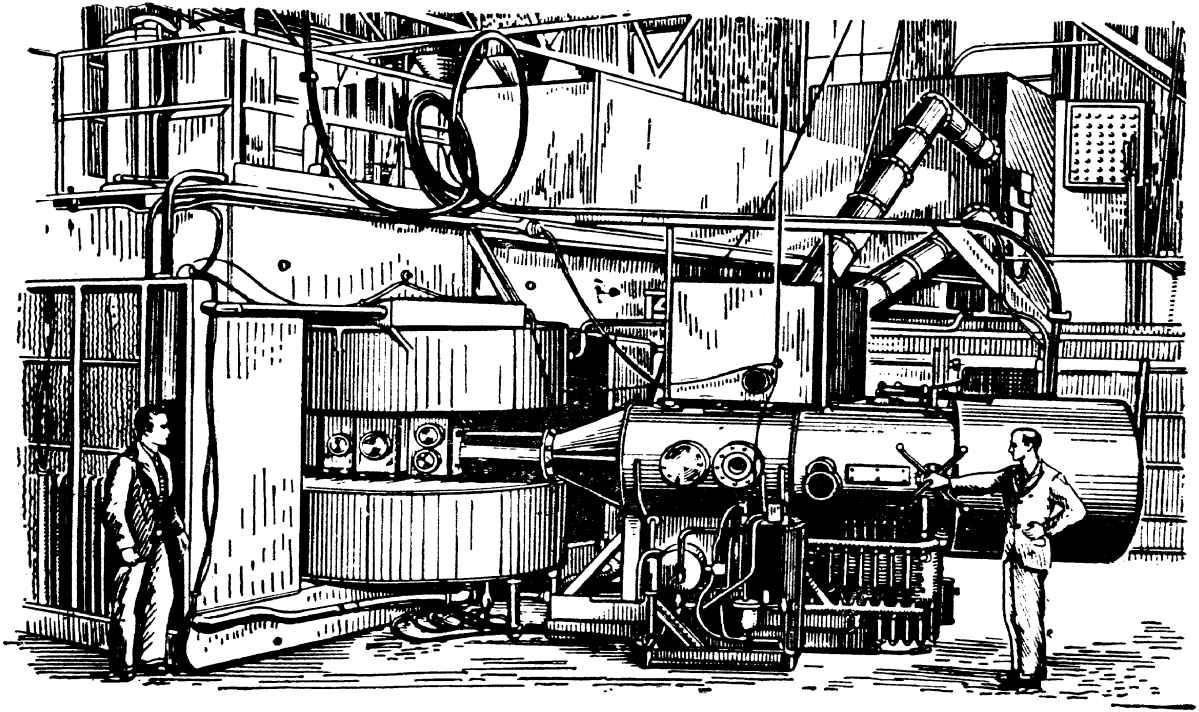


Fig. 31. General view of the cyclotron with 1.5-metre diameter pole pieces.

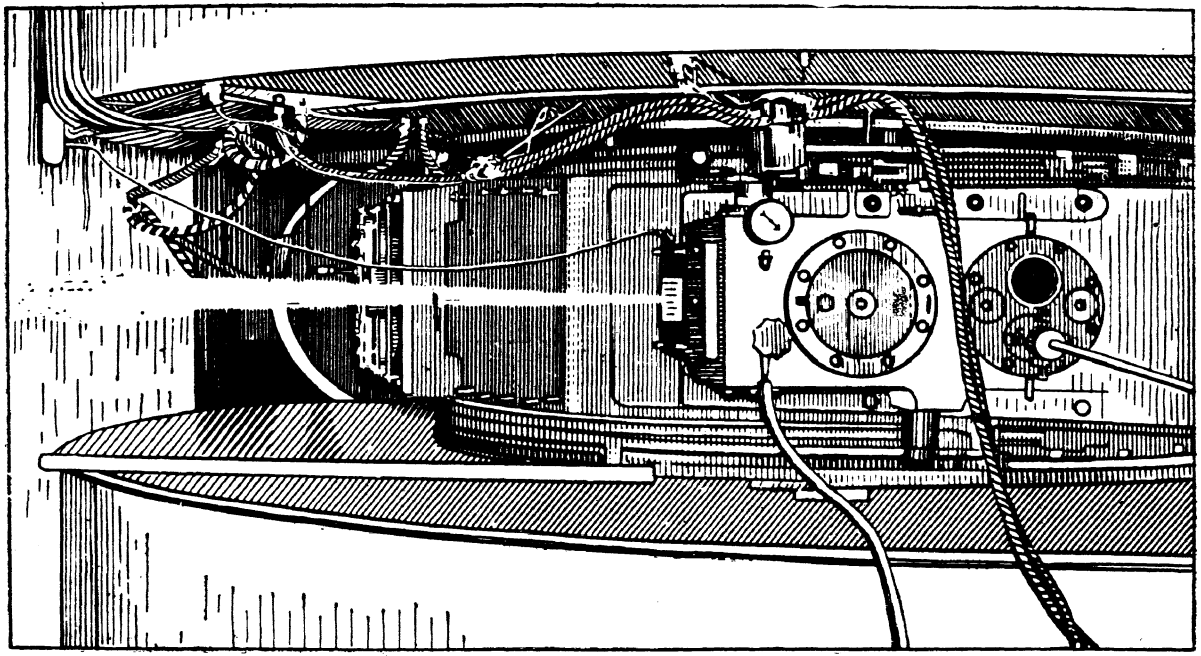


Fig. 32. Cyclotron with 1.5-metre diameter pole pieces. A beam of deuterons is seen with an energy exceeding 15 million electron-volts. It luminesces due to excitation of air molecules; the beam emerges from a window covered by a thin aluminium foil.

wise this particle will not be accelerated by the electric field, but will be retarded. Since the time interval during which the electric field changes is strictly constant, it is necessary that the period of motion of the particle should likewise be constant. But, as is seen from equation (10), the period of motion of the particle depends also on its mass. Now the mass of a particle is not a constant value. It is approximately constant only for low speeds, that is, in the case of small energies. Given sufficiently large energies, the mass of the particle begins to grow perceptibly. The greater the energy of the particle becomes, the greater the departure of the mass from the rest mass of the particle. The change in mass brings about a change in the period of its motion along the circle, which becomes larger and larger. The particle begins to lag in reaching the gap between the halves of the chamber where the electric field exists. This lag results at first in the particle passing the electric field not at the maximum potential but slightly later. It then receives less energy from the field. But subsequent lagging increases to such an extent that the particle begins to enter the electric field when the latter is turned in the opposite direction. The particle will then begin to lose the energy it has gained. In order to avoid this, the particle must be stopped after it has been accelerated to the energy at which its mass begins to change considerably.

This limit energy value is not the same for all particles. It depends on the speed of the particle, and hence on its mass. Thus, the mass of a proton changes perceptibly already at an energy of several million electron-volts. For this reason, to accelerate protons to an energy exceeding 10 million electron-volts, one has to resort to all kinds of tricks. Deuterons, which have masses greater than that of the protons, may be accelerated to still greater energies. It is still easier to obtain artificial high-energy alpha particles. Difficulties due to change of mass begin to be felt only during acceleration beyond energies of 20 million electron-volts.

Quite different is the situation with electrons. Their mass is small, nearly two thousand times less than that of a proton. Already at energies of 10 to 20 thousand electron-volts their velocity approaches close to that of light, and the mass change becomes noticeable as the energy of the electron

increases. It is obvious, therefore, that the cyclotron cannot be used to accelerate electrons.

For a long time it was thought that the only way to accelerate electrons was through the direct use of high potentials. However, in 1940, Kerst succeeded for the first time in accelerating electrons without applying a high voltage.

In his machine, Kerst utilized the phenomenon of electromagnetic induction. Recall what electromagnetic induction is. If we take a circular circuit (conductor) *ABC* (Fig.

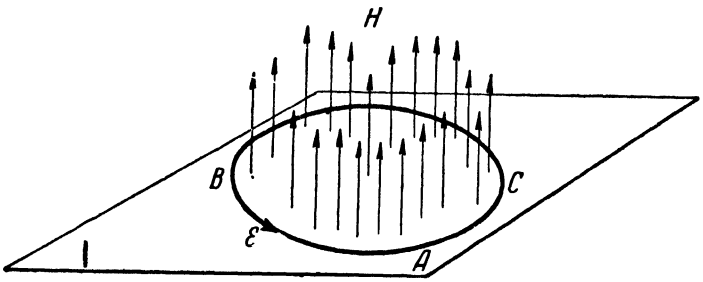


Fig. 33. When the magnetic flux varies in the circuit *ABC*, an electromotive force of induction arises.

33) and place it in an alternating magnetic field in such a way that the flux of magnetic lines of force passing through this circuit changes, a change of the magnetic flux will induce in circuit *ABC* an electromotive force of induction E which depends on the rate of change of the magnetic flux. The electromotive force produced in the circuit *ABC* is due to an electric field (the lines of force of which have the form of closed curves, for example, circles) appearing around a changing magnetic field.

If we force a charged particle to move along such a curve (for example, *ABC*), then during the whole time the magnetic flux changes it will gain speed, if the direction of its motion coincides with the direction of the lines of force of the induced electric field. After a complete cycle, this particle will have gained an energy equal to eE (e is the charge of the particle, E the magnitude of the electromotive force of induction). If we were able to compel the particle to move around the circle *ABC* twice, the acquired energy would

increase to $2eE$. In 10 revolutions the particle would have an energy of $10eE$ and so forth (on the condition, of course, that during this motion, the magnetic field changed at a constant rate).

To have the charged particle acquire more energy in each revolution, we must enlarge the circuit ABC and make the magnetic field change at a faster rate. However, even if the energy acquired by the charged particle during one revolution is small (only some few electron-volts), the particle may be accelerated to energies of several million electron-volts, if we make it do several million revolutions about the circle ABC.

Consequently, for the acceleration of charged particles by an induced electric field, these particles must make a large number of revolutions about a changing magnetic flux. We already know how to force a charged particle to move in a circle: *the trajectory of the particle must be in a magnetic field.* By selecting a magnetic field of proper size we will be able to make a particle of given energy describe a circle of given radius.

Thus to accomplish induction acceleration, two magnetic fields are required: one, a variable magnetic field, around which the particle moves (this field accelerates the particle); the other magnetic field must be along the trajectory of the particle (this field controls the motion of the particle making it move in a circle of given radius).

What kind of controlling magnetic field should there be? Obviously, it should also be variable in time. Indeed, the energy of a particle moving around an accelerating magnetic field constantly increases with time. If in this process the controlling magnetic field remained constant, the radius of the trajectory described by the particle would grow constantly with the acceleration of the particle just as in the case of the cyclotron. The change in the curvature radius of the trajectory of a particle moving with varying energy in a constant magnetic field is defined by equation (9) which we have already frequently made use of. This same equation indicates a way to make the charged particle move in a magnetic field in a circle of constant radius. What is required is that the increase in the energy of the particle be correlated with an increase in the intensity of the magnetic field such

that the ratio *mu/He* should remain constant. If we succeeded in doing this, the charged particle could move in a circle of a definite radius as long as the ratio *mu/He* remained constant.

For the ratio *mu/He* to remain constant, the following conditions are necessary:

1) the accelerating and controlling magnetic fields must vary in time according to one and the same law;

2) the intensity of the controlling magnetic field must be one half of the mean value of the intensity of the accelerating magnetic field.

Besides these conditions, acceleration requires that both magnetic fields change all the time in one and the same direction (for example, increase). This requirement is due to the direction of the induced electric field depending on the sign of the change of the magnetic field. When the magnetic field increases, the direction of the induced electric field will be the reverse of what it is when the magnetic field diminishes. If the accelerating magnetic field alternately increases and diminishes, the particle will also alternate in acceleration and deceleration. To obviate this, we must use a monotonically varying magnetic field. This circumstance imposes a certain limitation on the energy of the particle being accelerated for the simple reason that we cannot change the magnetic field monotonically an indefinite time. A magnetic field is capable of growing only to a certain value (if the magnetic flux is created in iron, the magnitude of the limit magnetic flux is determined by saturation of the iron). After this the magnetic field will either be constant or will begin to diminish, if we continue to feed the magnetizing winding with alternating current. Thus, in an induction accelerator, the process of acceleration must continue a very definite period of time, following which the particle must be removed from the accelerator, otherwise it will begin to decelerate.

How much energy will the particle succeed in accumulating during this time? Does this energy depend on the frequency of the alternating current? At first glance, it may seem that the higher the frequency of the alternating current, the greater will be the energy gained by the electron in the process of acceleration, because the higher the frequency, the faster the magnetic flux changes, and the faster the magnetic

flux changes, the greater the induced electromotive force, and with it the energy a charge acquires during one revolution about a varying magnetic field.

However, the frequency of the alternating current does not actually produce any effect on the final energy of the particle being accelerated. The energy a particle acquires during one revolution increases with the alternating-current frequency, yet since there is a limit on the increase of the magnetic flux imposed by saturation of the iron, this limit will be reached the faster, the higher the rate of growth of the magnetic field, and therefore the duration of acceleration of the charge will be less. And so, with a higher frequency of alternating current, the energy acquired by a charge during one revolution increases but the number of revolutions decreases. A more rigorous calculation shows that the maximum energy that a charge can acquire during such an induction acceleration does not depend on the frequency with which the magnetic field varies, but does depend on:

1) the absolute magnitude of the change of magnetic flux passing through an orbit described by a moving charge; the greater this change, the more energy the particle will acquire;

2) the time during which the particle makes one revolution. The greater the radius of this orbit, the more time will the particle spend in moving around the magnetic field (at the given maximum value of the flux) and the less will be the energy that it acquires as a result of acceleration. The mass of the moving particle will also affect the time of motion around the magnetic field. The greater the mass, the less the speed of the particle (at a given energy), and the less energy it will acquire during acceleration.

Thus, induction acceleration requires that we make the charged particles do a tremendous number of revolutions around a changing magnetic flux. It is quite natural that the particles must move in a good vacuum. Every encounter with air molecules will produce a change in the required ratio between the energy of the particle and the magnitude of the controlling magnetic field. For this reason, induction acceleration is done in a circular tube (having the form of a torus) that is highly evacuated by a system of vacuum pumps.

But all this is not yet sufficient for a particle to be able

to make several million revolutions without hitting the walls of the circular tube. Conditions had to be created that would make the motion of the charged particle stable. In the case of stable motion, a particle that has slightly departed from the correct path does not go astray altogether, but is automatically put back on the correct path. The lack of stability of motion was the chief cause for failures in early attempts with the induction accelerator. Kerst was the first to show that if the controlling field is made *to vary also in space*, and in such

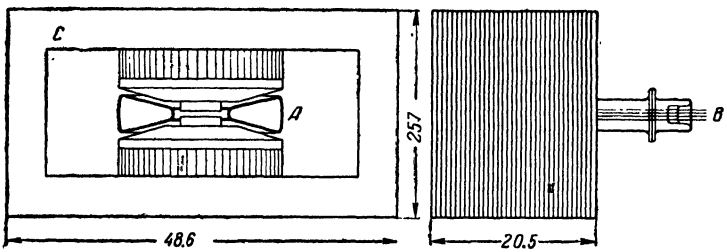


Fig. 34. Diagrammatic sketch of Kerst's first betatron which developed 2.3 million electron-volts (the dimensions are indicated in cm.). *A* — circular tube where electrons are accelerated; *B* — pipe into which is inserted a filament that radiates electrons; *C* — magnet core.

manner that it diminishes from the centre to the periphery, then the motion of particles in such a controlling field becomes stable, and they are capable of making a tremendous number of revolutions about the changing magnetic flux, and all in a definite orbit. The accepted term for this orbit is the equilibrium orbit.

Kerst's work was a success. The first machine in which electrons were accelerated to 2.3 million electron-volts, called a betatron, was so small that it easily fitted into a laboratory desk. The structure and size of this betatron is shown in Fig. 34. Fig. 35 gives a general view of it. In design, the betatron is much like an ordinary transformer, in which the secondary winding is removed and replaced by a circular chamber where the particles are accelerated.

The betatron is so simple, cheap and relatively easy to build that it has become an invaluable tool in the hands of the investigator. Scientists immediately began to study

and utilize the newly discovered possibilities. A year after the first betatron with its 2.3 million electron-volts was built, there appeared a betatron which accelerated electrons to energies of 20 million electron-volts.

In this betatron the radius of the equilibrium orbit is 19 cm. In the process of acceleration, the electrons make 350,000 revolutions covering a distance of about 420 km. At the present time, a betatron (shown in Fig. 36) has been built that imparts to electrons energies of 100 million electron-volts.

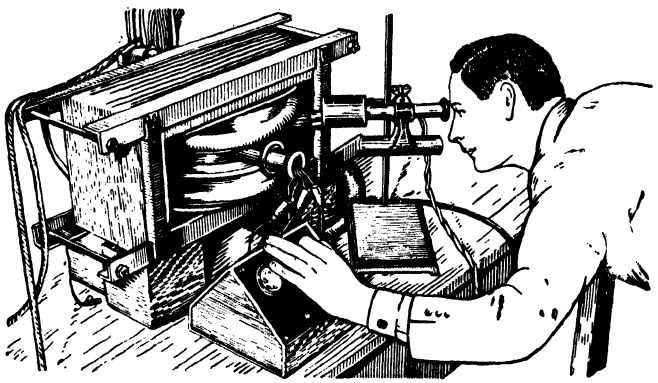


Fig. 35. General view of 2.3-million electron-volt betatron.

The betatron is a remarkable machine; its invention, together with the invention of the cyclotron, opened up a new stage in the study of the atomic nucleus. But it too has its restrictions. The betatron can only be used to accelerate light particles, such as electrons. It is not worthwhile accelerating heavy particles (protons, deuterons or alpha particles) with a betatron. Recall that the particles will be accelerated during a definite interval, during which time the particle must make a large number of revolutions. The greater the number of revolutions it makes, the greater will be the kinetic energy it gains. It is clear that the greater the mass of the particle, the lower will be its speed, at a given kinetic energy. Therefore, such a particle will spend more time in

making a revolution about the variable magnetic flux, and during the increase of the flux it will succeed in making a smaller number of revolutions; and this will result in less energy being acquired. For this reason, though the betatron is a very effective tool for accelerating electrons, it is poorly fit to accelerate the heavier particles.

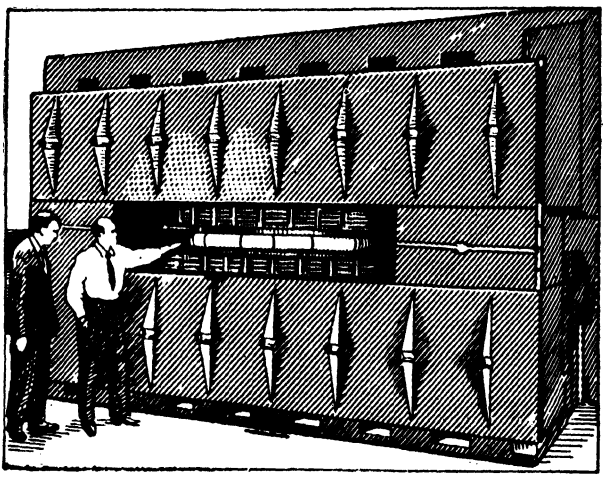


Fig. 36. General view of 100-million electron-volt betatron.

In view of the specific features of the cyclotron and the betatron, a peculiar "division of labour" has set in. The cyclotron is used to accelerate the "heavy" particles, and the betatron electrons.

The betatron has enabled large energies to be imparted to electrons. The possibilities of the betatron are in this respect incomparably greater than what the electrostatic generator can give. But they too have a limit. The existence of this limit was pointed out by the Soviet scientists D. D. Ivanenko and I. Y. Pomeranchuk. They noticed that electrons moving inside a betatron must, when moving in a circular orbit, radiate electromagnetic waves.* The greater

* From the laws of electrodynamics it follows that a charge undergoing acceleration should radiate electromagnetic waves.

the energy to which the electron has been accelerated, the greater the intensity of the waves it radiates. At very high electron energies, the radiation intensity becomes so great that the loss of energy by the electron (due to radiation) becomes comparable to the energy acquired by the electron from the varying magnetic field. Naturally, when the energy gain due to acceleration and the energy loss due to radiation become equal, the electron will no longer increase its energy. According to the first calculations, this limit sets in at approximately 500 million electron-volts. But, in actuality, as L. A. Artsimovich and I. Y. Pomeranchuk have pointed out, the electron will cease to gain speed in the betatron before the energy loss by the electron due to radiation becomes equal to the energy acquired by acceleration. To understand how radiation limits the energy to which an electron may be accelerated, recall that in the betatron an electron is always moving in a constant orbit (the so-called equilibrium orbit). This is possible because the magnetic field in which the electron moves increases with the energy of the electron. The energy variations of the electron must be strictly coordinated with changes in the magnitude of the magnetic field Equation (9) shows that the controlling magnetic field in the betatron must increase with the momentum of the electron. But due to radiation the energy of the electron will increase more slowly than is called for by the change in the magnetic flux. The momentum of the electron will increase more slowly than the controlling magnetic field. The magnetic field will begin to deflect the electron more strongly; this will result in the radius of its trajectory beginning to decrease, and instead of moving in an equilibrium orbit, the electron will begin to spiral into the centre. The more radiation there is, the faster it will spiral, and the electron will eventually plunge into the wall of the tube in which it is being accelerated.

A detailed analysis of the influence of radiation on the acceleration of electrons in a betatron was carried out by L. A. Artsimovich and I. Y. Pomeranchuk, and also by D. D. Ivanenko and A. A. Sokolov. They established that the energy lost in radiation depends on the radius of the equilibrium orbit and increases as the fourth power of the energy of the electron. Radiative losses of electrons acceler-

ated up to 100 million electron-volts are not great, and the radius of the equilibrium orbit changes only a few centimeters. However, further increases in the energy of the electron enlarge the radius of the equilibrium orbit to such an extent that the electrons begin to impinge on the walls of the tube.

Thus electrons accelerated in a betatron radiate *electromagnetic waves*. We have already pointed out (p. 78) that visible light also consists of electromagnetic waves of a very definite frequency range. Given certain conditions of acceleration, could not the electromagnetic waves emitted by electrons in the betatron become visible? Yes, this appears possible.

The frequency of the radiation emitted by an electron is a function of its energy over the equilibrium orbit. Given an equilibrium orbit radius of 30 cm., electrons accelerated to 30 million electron-volts should emit electromagnetic waves of a frequency of the order of 4×10^{14}. Rays of this frequency belong to the red part of the visible spectrum. When electrons are accelerated to 80 million electron-volts the frequency of the electromagnetic radiation reaches a value in the neighbourhood of 10^{15} to 10^{16}. These are rays from the ultraviolet part of the spectrum. The conclusion we arrive at is remarkable: electrons accelerated in a betatron to energies of several tens of millions of electron-volts should radiate visible light. They will become "luminescent" electrons. No involved techniques, such as the use of cloud chambers or Geiger-Müller counters, will be needed to detect such electrons, for they will be visible to the unaided eye.

The existence of such "glowing" electrons was soon confirmed. It was found that electrons accelerated to 30 million electron-volts begin to radiate visible light; the electron beam looked like a dark red strip. At 80 million electron-volts the electron beam was a brilliant shining strip of bluish white.

The invention of the betatron and cyclotron made it possible to accelerate charged particles (electrons, protons, helium ions) to exceedingly high energies. The limit to which particles could be accelerated by high-voltage machines (from three to five million electron-volts) was pushed forward a great distance. Charged particles could now be endowed with energies up to 100 million electron-volts. However, even this did not satisfy men of science. The discovery in

cosmic radiation of mesons and of strong interaction between mesons and atomic nuclei placed on the agenda the problem of building accelerators capable of accelerating particles to the cosmic level, that is, to energies in the vicinity of one thousand million electron-volts. This necessity spurred scientific workers to refine the accelerating principles of the cyclotron and the betatron.

New Types of Charged-Particle Accelerators

An interesting development of the principle of particle acceleration using an oscillating field was suggested by the Soviet physicist V. I. Veksler and, independently, by the American physicist McMillan. As has already been pointed out, the energy increase in the betatron is limited by loss of energy due to radiation. During its revolution around the magnetic flux, the electron acquires too little energy, only several electron-volts. Now, is it not possible to make the electron gain in one revolution not a few electron-volts but several thousand, that is, just as much as a charged particle acquires when accelerated in a cyclotron. If such were the case, the energy limitation for electrons would increase substantially. But it is impossible to accelerate electrons in a cyclotron because their mass varies with energy, and therefore, their period of revolution is not constant. However, already at an energy of one million electron-volts an electron attains a velocity only five per cent below that of light. Since the velocity of light is the limit for particle speeds, it is clear that any energy increase of the electron above one million electron-volts practically does not change its speed. This means that if an electron moves in a path of constant radius, it will cover the path in one and the same time. The constancy of the period of revolution makes possible acceleration by an oscillating field. Whence the concept of the synchrotron, a machine that combines the properties of the betatron and the cyclotron.

In a synchrotron, the electron is first accelerated just as in the betatron, that is, by an increasing magnetic field. When the electron energy reaches a value of the order of one million electron-volts, the system of acceleration by an oscil-

lating electric field is switched on just as in the cyclotron. The electron begins to gain energy from the oscillating electric field. The magnetic field is varied only insofar as is required for the electron to remain in a stable circular orbit. The synchrotron makes it possible to impart considerably greater energies to electrons than those obtainable in the betatron. The synchrotron is capable of accelerating electrons to energies of 200 to 300 million electron-volts.

The invention of the synchrotron has enabled the limit value of energy which may be communicated to electrons to be raised. But how is one to raise the level of energy imparted to such heavy particles as protons, deuterons and alpha particles? Veksler found a way to solve this problem too.

Recall once again that the acceleration limit of ions in a cyclotron is conditioned by the change of mass of the particle. The constant period of revolution, equal to $\frac{2\pi m}{eH}$ [equation (10)], is violated in the case of a change in mass; simultaneously the synchronism of the motion of the particle and the variation of the electric field is upset. Veksler was the one who pointed a way out of this impasse. He suggested varying the period of variation of the electric field according to the same law that governs the mass changes of the particle undergoing acceleration. Machines using this principle were called "synchrocyclotrons" (or frequency-modulated cyclotrons). The synchrocyclotron is capable of communicating much greater energies to heavy charged particles.

In 1949, a synchrocyclotron capable of accelerating protons to energies up to 680 million electron-volts was built in the Laboratory of Nuclear Problems of the U.S.S.R. Academy of Sciences under the leadership of M. G. Meshcheryakov, D. V. Yefremov and A. L. Mints. The synchrocyclotron of the Academy of Sciences is the largest of its type in the world.

The building of a synchrocyclotron is a very complex undertaking. Suffice it to say that the pole pieces of the magnet of the Academy synchrocyclotron are nearly six metres in diameter. Much labour and money is required to set up a magnet of this size. The synchrotron is a simpler machine because the particle in it is accelerated all the time in an equilibrium orbit. For this reason, there is no necessity to

create a magnetic field through the space inside the equilibrium orbit. It is enough to establish a magnetic field only on the orbit itself and in its immediate vicinity. This greatly lightens the magnets designed for accelerating particles to very high energies. Their volume and cost are cut drastically. A high-energy synchrotron will cost much less than a synchrocyclotron.

However, a very natural question comes to mind: We said that the synchrotron is designed for accelerating electrons, but can the synchrotron be used to accelerate heavy particles (protons, or helium nuclei) as well? It turns out that this is possible. All that is needed is to modify the process of acceleration.

We have already pointed out that the chief difficulty in accelerating heavy particles in an induction accelerator is that the heavy particles move more slowly and their period of revolution is too great, the result being that during the time required for the magnetic flux to change, the energy gained is too little. But in the synchrotron, the particles are accelerated chiefly not by the induction method but by an oscillating electric field. Therefore, the energy accumulated by a charged particle (a proton or alpha particle) is no longer related to the variation time of the magnetic flux.

How is it possible to apply an oscillating field to the acceleration of protons? You will remember that we stressed the point that acceleration by an oscillating field is based on the approximate constancy of velocity of the high-energy electrons (or, to be more precise, on the fact that their speed is practically independent of energy); however, the velocity of heavy particles in the energy range up to 100 million electron-volts varies very considerably with energy and it proves impossible to obtain an equilibrium orbit. To apply to protons the acceleration technique of the synchrotron we must give them an energy of several tens of millions of electron-volts, and only then accelerate them by an oscillating electric field. The initial acceleration of heavy particles may be done by the procedure used in the synchrocyclotron, that is, by acceleration of the particle by an oscillating field, the frequency of which varies in such a way as to ensure synchronism between the motion of the particle and the accelerating oscillating electric field.

The synchrotron, as we see, possesses universal properties. It is capable not only of accelerating electrons to high energies, but also of accelerating protons. And what is more, the proton acceleration in the synchrotron is not restricted by radiation since the intensity of the electromagnetic waves emitted by a charged particle undergoing acceleration is inversely proportional to the fourth power of its mass. Consequently, radiation of protons will be by a factor of 10^{12}—10^{13} less than the radiation of electrons. This means that it may be ignored even at energies up to hundreds of thousands of millions of electron-volts.

When accelerating protons to energies greater than a thousand million electron-volts, it is better to use an oscillating electric field whose frequency may be slightly varied (as is done in the synchrocyclotron).

A machine which accelerates a particle by an oscillating electric field with varying frequency while the particle is kept in an orbit of constant radius by a magnetic field which is variable in time is known as a "proton synchrotron." To give the reader an idea of what these machines are like that accelerate particles to energies of thousands of millions of electron-volts, we shall describe two accelerators, the Brookhaven proton synchrotron built in the U.S.A. in 1953, and called a "cosmotron" (because it is capable of imparting to particles energies that are met with in cosmic rays), and the Soviet proton synchrotron of the electrophysics laboratory of the U. S. S. R. Academy of Sciences.

A diagram of the cosmotron is given in Fig. 37. The chamber of the accelerator is a circular tube with a rectangular cross section. The average radius R of this tube is 9 m. The circle with this radius is the equilibrium orbit. The circular tube is 75 cm. in width. The chamber is situated between the poles of a circular electromagnet. The magnet of the cosmotron is not solid but consists of four sections. Between these sections the particle moves in straight lines, each of which has a length of three metres.

The particle is accelerated in the gaps marked C. Here it passes through an electric field $E=E_0 \sin \omega t$, its frequency ω being selected such that the particle should traverse this field at definite instants of time when the direction of the

field coincides with the direction in which the particle is moving.

Protons are injected into the cosmotron at an energy of 3.5 million electron-volts, which they acquire from an electrostatic generator *A*. The big initial energy of the protons greatly simplifies their subsequent acceleration. At an energy of 3.5 million electron-volts a proton has a velocity one-tenth that of light. For this reason, the frequency of revolu-

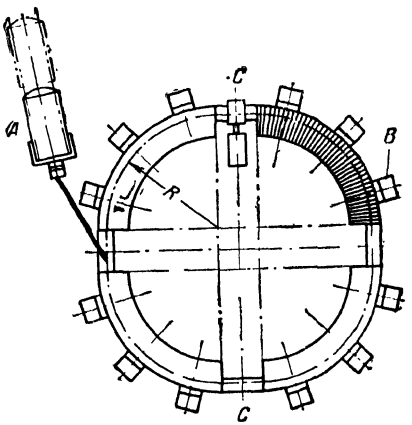


Fig. 37. Plan view of the Brookhaven cosmotron.

tion of the protons will no longer vary appreciably in the case of continued acceleration. In the Brookhaven cosmotron, the frequency with which the accelerating oscillating field varies changes from 370,000 (beginning of acceleration) to four million cycles per second (end of acceleration). The frequency is varied synchronously with the variation of proton energy so that the protons should move close to the equilibrium orbit. In the process of acceleration, protons complete nearly three million revolutions, acquiring during each revolution an energy equal to 800 electron-volts. Each section of the magnet is made up of 864 separate laminations each 12.5 mm. in thickness. The whole magnet weighs nearly 2,000 tons. The magnetizing winding of the magnet

consists of 48 water-cooled turns through which currents up to 7,000 amperes are passed. A whole electric power station is required to feed this magnet, which consumes 26,000 kilovoltamperes.

Twelve powerful diffusion pumps are used to create the necessary vacuum in the chamber. In Fig. 37, one of these pumps is indicated as *B*. The diffusion pumps of the cosmotron are capable of evacuating as much as four cubic metres of air every second. The volume of the acceleration chamber comes to nearly 33 cubic metres.

A general view of the Brookhaven cosmotron is shown in Fig. XXV in the Appendix. In the Brookhaven cosmotron protons can acquire an energy up to 2,900 million electron-volts.

The most powerful proton synchrotron in the world was placed in operation in April 1957 in the Soviet Union. In it, proton energies up to 10,000 million electron-volts have been obtained. The building of this accelerator is an outstanding scientific and engineering feat. It was built in the electrophysics laboratory of the Academy of Sciences of the U.S.S.R. under the leadership of V. I. Veksler, D. V. Yefremov and A. L. Mints.

The circular magnet of the Soviet proton synchrotron has a diameter of about 60 metres and weighs 36,000 tons. Protons speeded in a linear accelerator to an energy of nine million electron-volts are injected into the acceleration chamber of the machine. The plant that supplies the electromagnet with current has a power of 140,000 kilowatts. Fifty-six powerful pumps are used to evacuate the air from the acceleration chamber.

A general view of this synchrotron is shown in Fig. XXVI in the Appendix.

At the present time work is in progress in the Soviet Union on still more powerful accelerators capable of speeding protons to energies of 50,000 million electron-volts.

Chapter VII

ARTIFICIAL RADIOACTIVITY

The Discovery of Artificial Radioactivity

The year 1934 was marked by a new and important discovery, the credit for which goes to Frédéric Joliot and Irene Curie. This is how it happened.

In Chapter IV we wrote about the discovery of neutrons. Neutrons were detected in the action of alpha particles on beryllium. The Joliots (Frédéric and Irene) began a systematic study to find out what substances emit neutrons under bombardment of alpha particles. They found that when alpha particles bombard such materials as aluminium and magnesium, neutrons are produced.

The emission of neutrons by aluminium was particularly interesting. This interest was due to the fact that aluminium (as had been well known from the time of the first experiments in splitting nuclei) emits protons when bombarded by alpha particles. The formation of silicon was the result of the transformation of the aluminium nucleus. Here is the scheme of this transformation:

$$_{13}Al^{27} + {}_{2}He^{4} \longrightarrow {}_{14}Si^{30} + {}_{1}H^{1}.$$

It now appeared that when bombarded with alpha particles, aluminium emits not only protons but also neutrons. If aluminium consisted of a mixture of several isotopes, this result would be no cause for surprise. It might be thought that different isotopes are transformed by alpha bombardment in different ways, some isotopes emitting protons in the transmutation process, others neutrons. But it is well known that aluminium has only one isotope. This means that both neutrons and protons are sure to appear in the transformation which aluminium-27 nuclei undergo.

Two different particles shooting out of one nucleus was something quite new. Two suppositions could be made in this respect.

1) A neutron and a proton arise from the aluminium nucleus simultaneously. If this is so, then the tranformation scheme of an aluminium nucleus proposed by Rutherford is incorrect. The nuclear reaction should proceed otherwise, namely:

$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{14}Si^{29} + _{1}H^{1} + _{0}n^{1},$$

that is, the transformation product would also be an isotope of silicon, but 29, not 30.

2) Neutrons arise independently of protons, in which case there should exist two different ways of transforming aluminium nuclei. We already know one of them, it leads to the formation of a proton; the other may be written as:

$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{15}P^{30} + _{0}n^{1}.$$

This results in the formation of a neutron. Some nuclei are transformed in one way, others in the other.

In order to decide which of these two suppositions is correct, a further study had to be made of the transformations of aluminium nuclei under the action of alpha particles. The Joliots were the ones who undertook this study. They placed aluminium in a cloud chamber and began observing the tracks of particles produced in the transformation of its nuclei. Aside from the heavy tracks which may naturally be ascribed to protons they very unexpectedly noticed thin lines that resemble the tracks of electrons. The nature of these electrons was not clear. And so they decided to put their cloud chamber in a magnetic field and repeat the investigation. In the magnetic field, the tracks of the particles bent, but not as electrons would have done. The tracks curved in a direction that corresponded to a positive charge. From an analysis of their photographs Joliot and Curie could see that the particles forming these tracks were positrons. This was a startling result: it turned out that positrons, which had been just before discovered by Anderson in cosmic radiation, can also originate on the earth. However, this conclusion was not the only result of the Joliot-Curie experiments.

Let us return again to the transformation of aluminium. Did the Joliot-Curie experiments resolve the question of the character of the transformation of aluminium? At first glance, it seemed that far from resolving it, they even brought new complications, because under alpha bombardment an aluminium nucleus ejects not only protons and neutrons but also positrons. The problem now to be solved was: Do all these three particles arise at once, or separately, or maybe two of them shoot out of the nucleus simultaneously? Joliot rejected the possibility of the simultaneous ejection of all three particles (protons, neutrons, and positrons) from an aluminium nucleus. Such a process would energetically have too many disadvantages. He noted the act that a positron and neutron together possess the same charge and roughly the same mass as a proton. This was enough to surmise the existence of the following modes of transformation of aluminium:

$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{14}Si^{30} + _{1}H^{1}.$$
$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{14}Si^{30} + _{0}n^{1} + _{+1}e^{0} \text{ (positron).}$$

The result of both transformations is the formation from aluminium of one and the same substance, silicon-30. The only thing is that protons are ejected in one transformation, and two particles (a positron and neutron) in the other. Joliot's assumption looked very much like the truth; but subsequent investigations showed that it was not exactly correct. Quite unexpectedly it was found that positrons arise not only during the bombardment of aluminium by alpha particles but also some time afterwards. For example, it was found that if aluminium is irradiated with alpha particles and the alpha source is then removed, the emission of protons and neutrons will cease immediately, whereas positrons continue to be emitted. But their number gradually diminishes. Every $3\frac{1}{4}$ minutes the quantity of positrons emerging (in unit time) from the aluminium decreases by a factor of two.

This was very much like the phenomenon of radioactive decay, the only difference being that in the process of this decay positrons are produced and not electrons or alpha par-

ticles. The half-life of $3\frac{1}{4}$ minutes likewise differed from the half-lives of earlier known radioactive transformations. And finally, the most remarkable thing was that this radioactive decay did not arise spontaneously; it was produced wholly by the experimenters.

The production of neutrons and positrons was discovered not only in the case of aluminium. Joliot and Curie found that boron and magnesium likewise emit both neutrons and positrons during alpha-particle bombardment. Of course, the immediate task was to find out how these substances behaved. Do they exhibit radioactive decay or not, that is, do positrons appear after irradiation with alpha particles? Experiments showed that there is positron radioactive decay both in the case of boron and magnesium. When boron was irradiated with alpha particles and then the alpha source removed, it was noticed immediately that positron emission did not cease but continued with a gradual diminution of intensity. In the case of boron, the number of positrons decreased more slowly than for aluminium. Only fourteen minutes later was the number of positrons emerging in unit time reduced by one half.

Magnesium behaved similarly. It also emitted positrons after bombardment with alpha particles. The radiation intensity decreased one half in two and one-half minutes.

In short, induced, artificial radioactive decay was a fact. The phenomenon, which scientists at the beginning of this century were unable to influence in any way, was produced artificially in the laboratory in 1934. Joliot and Curie obtained three artificial radioactive substances:

from aluminium (half-life: 3.25 minutes)
from magnesium (half-life: 2.5 minutes)
from boron (half-life: 14 minutes)

What was the cause of artificial radioactive decay? What substances disintegrated? Clearly, it was not aluminium, or boron, or magnesium, for it was well known that prior to irradiation with alpha particles these substances showed no signs whatsoever of radioactive decay. It was obvious beyond all doubt that these were some kind of new substances, theretofore unknown.

The assumption that neutrons and positrons appear at one and the same time was obviously erroneous. Positrons appeared after irradiation, while neutrons and protons were observed only during irradiation of the substances with alpha particles. If neutrons and positrons appear separately, their appearance may be described by successive nuclear reactions. Thus in the case of aluminium, neutrons arise from the transformation:

$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{15}P^{\circ 0} + _{0}n^{1}$$

as a result of which the isotope phosphorus-30 is produced. But phosphorus-30 is not to be found among the stable isotopes. Only one isotope of phosphorus is known, phosphorus-31. For this reason, Joliot decided that if phosphorus-30 is Bot among the known stable isotopes, it must be unstable and should disintegrate, and the result is a positron. Thus positrons appear as a result of the radioactive decay of the unstable isotope of phosphorus-30*

$$_{15}P^{0*} \longrightarrow _{14}Si^{30} + _{+1}e^{0}.$$

We have nearly arrived at the earlier conclusion: both transformations of the aluminium nucleus lead to the formation of one and the same isotope of silicon; but in one case the transformation into the silicon isotope takes place at once (with proton emission) and in the other case it proceeds the complicated way, producing first the unstable isotope phosphorus-30 and then, after ejection of a positron, the final stable product, silicon-30.

The same also goes for magnesium and boron. Unstable isotopes are produced in the transmutations of these substances likewise. In the case of magnesium, the transformation proceeds as follows:

$$_{12}Mg^{24} + _{2}He^{4} \longrightarrow _{14}Si^{27*} + _{0}n^{1}.$$

Silicon-27 is not stable (three stable isotopes of silicon are known: silicon-28, silicon-29, and silicon-30). The unstable silicon isotope gradually decays, producing positrons. The decay scheme looks like this:

$$_{14}Si^{27*} \longrightarrow _{13}Al^{27} + _{+1}e^{0}.$$

* In future we shall use an asterisk to distinguish radioactive isotopes.

The decay scheme of boron is represented as:

$$_5B^{10} + _2He^4 \longrightarrow _7N^{13*} + _0n^1.$$

The unstable nitrogen isotope (nitrogen-13) disintegrates and becomes a stable isotope of carbon:

$$_7N^{13*} \longrightarrow _6C^{13} + _{+1}e^0.$$

This was the explanation given to the appearance of positrons in the case of aluminium, magnesium and boron. The earlier unknown unstable isotopes of phosphorus, silicon and nitrogen were responsible for the radioactive positron decay.

F. Joliot realized the extreme importance of this discovery and decided to confirm the existence of these new radioactive isotopes by direct experiments. He was out to prove by direct experimentation that, for example, in the bombardment of aluminium with alpha particles, phosphorus is really produced. To do this, he used the same technique as Ramsay had once done in studying the chemical properties of radium emanation. The Joliot experiments, however, were still more difficult since he had at his disposal no more than some ten thousand atoms of the new substances. And it was with this vanishingly small quantity that weighed something like 10^{-18} gram, that different chemical manipulations had to be carried out. This was possible since radioactive substances themselves give notice of their whereabouts; they disintegrate and the disintegration of each individual atom may be detected.

Assuming that irradiation of aluminium with alpha particles produces phosphorus, Joliot performed with the alpha-bombarded aluminium the chemical operations required to separate phosphorus from it. If his hypothesis was correct, then where the phosphorus should be, we should find a substance, the decay of which is accompanied by positron emission. This is exactly what happened. He performed various chemical manipulations and convinced himself that the material emitting positrons is chemically different from aluminium and silicon but absolutely identical with phosphorus. This was proof of the correctness of Joliot's hypothesis.

There follow from these studies conclusions of extraordi-

nary significance. Some will be considered later on, and some may be formulated here:

1) An unstable radioactive state of a substance may be induced artificially. In certain cases it is the result, for example, of alpha particles penetrating into the nucleus.

2) Not only the heavy elements at the end of the Periodic Table can be radioactive. Joliot and Curie proved that light elements such as nitrogen, phosphorus and silicon are also capable of existing in an unstable radioactive state.

3) Ordinary stable elements (phosphorus, nitrogen, silicon) have radioactive isotopes. It is possible (later we shall see that this is precisely the case) that other elements can also have radioactive isotopes, which we do not detect for the simple reason that they have long since disintegrated.

4) Nuclear transformation can proceed in several ways; for instance, aluminium-27 bombarded by alpha particles converts either into silicon (one way) or into phosphorus (another way).

Artificial Radioactivity Induced by Neutrons

The discovery of "artificial radioactivity," that is, the artificial production of radioactive substances, was an outstanding event. It excited a broad interest in the subject and focussed on it the attention of broad circles. It is of course quite natural that after Joliot and Curie established the existence of radioactive phosphorus, silicon and nitrogen, the question arose as to whether these artificially obtained radioactive substances were a special exception to the rule, or maybe other elements could also be produced in the form of radioactive substances. Are artificially radioactive substances produced only by alpha particles, or can other particles, such as protons and neutrons, be used for this purpose?

In the middle of 1934, the Italian physicist Fermi and his co-workers obtained convincing proof that many stable elements are capable of having radioactive isotopes.

Fermi irradiated different substances with neutrons, not alpha particles. His reasoning was this.

We know very well that alpha particles find it difficult to penetrate into atomic nuclei. The repulsive forces interacting between the alpha particle and the nucleus are the cause. It is precisely for this reason that alpha particles emitted by naturally radioactive substances are capable of producing nuclear transformations only in light elements, the nuclei of which possess a relatively small charge. Neutrons are something quite different. They have no difficulty in penetrating into nuclei. We may say that once inside a substance, a neutron will sooner or later and without fail penetrate into some atomic nucleus. The experiments described in Chapter IV are a clear-cut demonstration that neutrons interact with nuclei very effectively. For them, there is no difference between entering a light nucleus with a small charge or the very heaviest nuclei; in both cases they produce nuclear transformations.

Is it not possible that some of these transformations could lead to the formation of artificially radioactive substances similar to those obtained by Joliot? That was the question posed by Fermi and his collaborators. They bombarded over sixty different elements with neutrons. The neutron source in these experiments was an ampoule containing beryllium powder and radium emanation. To find out whether the neutron irradiation had produced a radioactive substance, the irradiated plate was brought close to a Geiger-Müller counter a little while after irradiation.

If the transformation produced by the neutrons led to the formation of radioactive substances, the counter would register the radiation that they emit in the process of decay. That is exactly what happened. When tested, certain substances were found to emit rays registered by counters long after irradiation had ceased.

Furthermore, it was found that in nuclear transformations radioactive substances are rather frequently produced. Thus 40 out of 60 investigated elements were radioactive after irradiation with neutrons. Special experiments (the action of a magnetic field on radioactive radiation) showed that electrons are emitted in all cases, but the possibility that some of the elements investigated emitted positrons during disintegration was not excluded. The half-lives were measured in nearly all cases where radioactive substances

were formed. They were found to range from several seconds to many days for different substances. Fermi's early studies did not give evidence of very long half-lives. This was apparently due to the fact that the intensity of radioactive radiation in such substances is not great.

In determining the character of nuclear transformations resulting from neutron capture, Fermi made use of chemical analysis much like that applied by Frédéric Joliot to determine the nature of radiophosphorus. Seeing that the radioactive element being formed is a close neighbour (in the Periodic Table) to the irradiated element, and hence has an atomic number close to it, he determined the nature of the bearer of radioactivity by identifying it with one of the elements adjacent to the irradiated one.

To do this, one of the neighbours of the irradiated element was added in turn to the latter and then both elements were separated chemically. After separation, a Geiger-Müller counter was used to determine what element was separated with the radioactive substance. Applying a series of successive operations it was always possible to establish that the radioactive substance follows a definite element. This was how the nature of the radioactive substance was determined. The following conclusions may be drawn from Fermi's work.

1) Neutrons *do* penetrate into the nuclei of a large number of elements. No difference is observed between light and heavy nuclei. Both are capable of producing radioactive substances.

2) A radioactive isotope may be formed in several ways. One way is by nuclear capture of a neutron with subsequent ejection of an alpha particle. This is the way radioactive sodium is produced from aluminium:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{11}Na^{24*} + {}_2He^4.$$

A radioactive substance may also be formed from a nucleus that has captured a neutron if the transformation is accompanied by ejection of a proton. This, for example, is the way radioactive silicon is produced from phosphorus:

$$_{15}P^{31} + {}_0n^1 \longrightarrow {}_{14}Si^{31*} + {}_1H^1.$$

And, finally, radioactive substances may form when no particle is ejected from the nucleus that captures a neutron. An illustration of this type of transformation is:

$$_{53}J^{127} + {}_0n^1 = {}_{53}J^{128*}.$$

This last type of radioisotope formation is especially noteworthy. This is the first case among many known nuclear transformations in which the whole act is simply the capture of a particle; therefore, the reliability of the evidence brought forward to confirm this scheme is especially important. Fermi made his deduction concerning the character of the transformation of iodine by the method of exclusion on the basis of chemical data which indicate that the radioisotope can be neither antimony (the ejection of alpha particles) nor tellurium (the ejection of a proton). The same technique was used to establish the nature of the transformations of copper, vanadium, manganese, arsenic, bromine, silver, iridium and gold. In this case, the radioactive substances are also formed by nuclear capture of a neutron *with no attendant ejection of another particle* (a proton or alpha particle).

Very often, the transformation of a nucleus that has captured a neutron proceeds in several ways.

For instance, aluminium nuclei that have captured a neutron convert in part with the emission of alpha particles:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{11}Na^{24*} + {}_2He^4,$$

in part with the emission of protons:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{12}Mg^{27*} + {}_1H^1$$

and partially by direct capture of a neutron by the nucleus:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{13}Al^{28*}.$$

In certain cases, all three possible modes of transformation into a radioactive isotope have been recorded, namely:

$$\begin{aligned}
&{}_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{11}Na^{24*} + {}_2He^4,\\
&{}_{12}Mg^{24} + {}_0n^1 \longrightarrow {}_{11}Na^{24*} + {}_1H^1,\\
&{}_{11}Na^{23} + {}_0n^1 \longrightarrow {}_{11}Na^{24*},\\
&{}_{27}Co^{59} + {}_0n^1 \longrightarrow {}_{25}Mn^{56*} + {}_2He^4,\\
&{}_{26}Fe^{56} + {}_0n^1 \longrightarrow {}_{25}Mn^{56*} + {}_1H^1,\\
&{}_{25}Mn^{55} + {}_0n^1 \longrightarrow {}_{25}Mn^{56*}.
\end{aligned}$$

3) There exists an essential difference in the character of the transformations observed in heavy and light elements. In the light elements radioactive isotopes are usually formed by the emission of either an alpha particle or a proton. In the heavy elements, however, radioactive isotopes are chiefly produced by direct capture of the neutron. This is not accidental and indicates that it is not only difficult for charged particles (protons and alpha particles) to enter an atomic nucleus, but it is also hard to get out again. The greater the charge of the nucleus, the more energy the alpha particles and protons must have to leave the nucleus. That was why Fermi was not able to observe, in the case of heavy elements, such formation of radioactive substances as is due to the ejection of alpha particles or protons. The smaller the energy of the neutrons used to bombard the nuclei, the lighter are the elements in which these neutrons can induce artificial radioactivity by the ejection of an alpha particle or proton. Conversely, if very high-energy neutrons are used in bombardments (such experiments were subsequently carried out), then the heavy elements will also exhibit artificial radioactivity produced by the ejection of an alpha particle or proton from a nucleus that has captured a neutron.

The situation is quite different with those radioactive substances which are formed by the direct capture of a neutron. To penetrate into nuclei, neutrons do not have to have any very considerable energy, because they are unaffected by the electric forces of repulsion when they approach a nucleus. For this reason, it might be supposed that even the very slowest neutrons would be able to induce radioactivity, that is, form a radioactive isotope by penetrating the nucleus.

To test this idea, Fermi performed new experiments that led to extremely interesting results.

Thermal Neutrons

First, we shall explain how low-energy neutrons were obtained. Fermi used the most widespread method at that time of producing neutrons from beryllium by irradiating it with alpha particles. The neutrons obtained in this way

have tremendous energies measured in millions of electron-volts.

How was one to reduce the energy of these neutrons?

Here is what Fermi did. It is known that not in every collision is the neutron captured by a nucleus. When we say that a neutron easily penetrates into an atomic nucleus, we are simply comparing a neutron with an alpha particle or a proton. Actually, however, by far not in every collision is a neutron captured by a nucleus. The usual thing is for a neutron to experience several collisions with different nuclei before being captured.

Now what happens when a neutron collides with a nucleus and is not captured? We spoke of this earlier, in Chapter IV. In such an encounter the neutron communicates a part of its kinetic energy to the nucleus with which it collides. The energy of the neutron is reduced. After a number of such collisions, the energy of the neutron may diminish considerably. This reduction in neutron energy will be particularly great in collisions with the nuclei of hydrogen atoms. Under appropriate conditions of encounter, the neutron may impart to the hydrogen nucleus its entire kinetic energy. Such cases, however, are rare. In the majority of cases, the neutron loses less energy in a collision. Precise calculations show that *on the average* a neutron, after an encounter, has only about one-third of its original energy E (or to be more precise, $\frac{1}{2.718}E$). If neutrons experience two collisions with protons, their mean energy afterwards will be equal to $\left(\frac{1}{2.718}\right)^2 E$. After the tenth collision the mean energy of the neutrons will be roughly one twenty-thousandth of the original energy.

This peculiarity of neutron collisions with protons was made use of by Fermi in order to obtain low-energy neutrons and observe their effect on the atomic nuclei of different elements. To do this, he surrounded the neutron source with a layer of paraffin or water several centimetres in thickness. Outside he placed the substance under investigation (Fig. 38). The thickness of the paraffin layer P was selected such that a neutron should experience several tens of collisions with hydrogen nuclei before reaching the substance under

study M. As a result of such a number of collisions, the energy of the neutron fell so substantially that the initial value of several million electron-volts became comparable with the energy acquired by the atoms of different substances due to thermal agitation (a small fraction of an electron-volt).

These slowed-down neutrons were later given the name of *thermal neutrons*, which was to emphasize that the energy of such neutrons corresponds to the energy of thermal agitation.

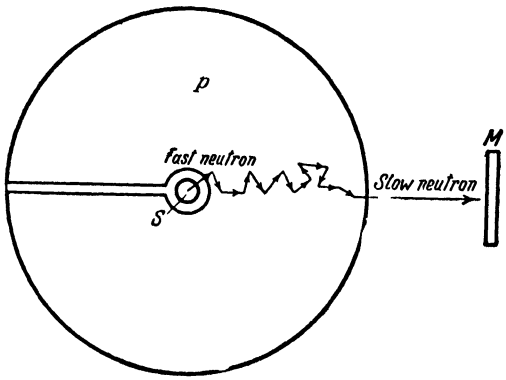


Fig. 38. Experimental arrangement for slowing down neutrons. S — neutron source (ampoule containing beryllium and radium emanation); P — paraffin; M — substance under investigation.

When Fermi began to determine whether thermal neutrons excite radioactivity, he at once discovered that those radioactive isotopes, that are formed by ejection from the nucleus of an alpha particle or a proton, are not produced by thermal neutrons. He was unable to detect such radioactivity by any methods. However, transformations involving only neutron capture were induced by thermal neutrons, too. And what is more, thermal neutrons produce such transformations much more efficiently than neutrons with a high kinetic energy. Especially effective was the action of thermal neutrons on certain substances, such as indium, rhodium and silver. The efficiency with which radioactivity is induced in these substances by thermal neutrons was so great that the former began to be used as indicators of the presence of thermal neutrons.

To characterize the great probability of capture of thermal neutrons by the nuclei of rhodium, we may make the following comparison: the quantity of fast neutrons falls off by one half in passing through approximately 10 cm. of lead, whereas one half of the thermal neutrons are captured by a rhodium plate only $\frac{1}{4}$ mm. in thickness. This comparison shows that thermal neutrons are very effectively captured by the nuclei of certain elements. This circumstance played an outstanding role in the development of nuclear physics and is of tremendous importance in the practical utilization of nuclear energy.

Neutron Capture That Does Not Lead to Radioactivity

A neutron that enters a nucleus changes the properties of the latter. Even if no particle is ejected from the bombarded nucleus and the charge of the nucleus does not change, still the nucleus is different.

We already know that a nucleus that has captured a neutron becomes radioactive. But is this always the case? Is it not possible for a neutron, say a thermal neutron, to be captured by a nucleus without forming a radioactive isotope?

Fermi resolved this problem too. He made use of the fact that thermal neutrons are very effective against rhodium, endowing the latter with radioactive properties. Observing the appearance of radioactivity in rhodium, it is possible to detect exceedingly weak beams of neutrons. This is why Fermi selected rhodium plates as thermal neutron indicators. He interposed a paraffin block P between the rhodium plate R and the neutron source S to slow down the neutrons; and between the paraffin and the rhodium plate he placed sheets M of different substances (Fig. 39).

Fermi reasoned this way: if a substance absorbs thermal neutrons readily, then a sheet of such a substance placed between a source of thermal neutrons and a rhodium plate will reduce the flux of thermal neutrons impinging on the plate of rhodium. If in this process we do not detect, in the sheet that is absorbing the thermal neutrons, any formation of

radioactive substances, this will mean that due to capture of a neutron by a nucleus there is formed a stable isotope of the substance under investigation instead of a radioactive isotope.

Using the foregoing method to investigate the absorption of thermal neutrons, he found that certain substances, such as boron, cadmium, yttrium, iridium and others absorb thermal neutrons more strongly than rhodium. For example, a layer of boron $\frac{1}{10}$mm. in thickness absorbs thermal neutrons

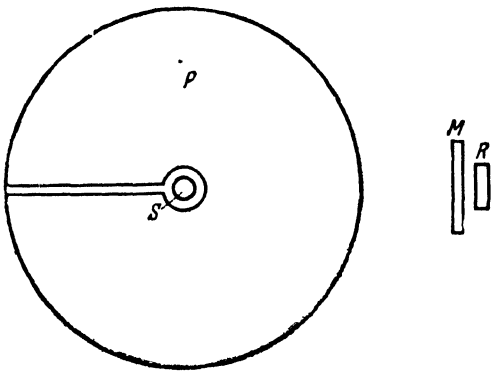


Fig. 39. Measuring slow-neutron absorption that does not lead to the creation of a radioactive isotope. *S* — neutron source; *P* — paraffin; *M* — substance under investigation; *R* — rhodium detector.

almost completely, although no radioactive substance is produced in the process. Since boron has only two isotopes, it was easy to decide which of them remained stable after the capture of a neutron. Obviously, it should be the light isotope of boron, B^{10}. Boron-10 captures a neutron and converts into another stable isotope of boron, B^{11}:

$$_5B^{10} + _0n^1 \longrightarrow _5B^{11}.$$

Because of the ability of boron, and especially cadmium, to absorb thermal neutrons strongly, these substances subsequently found broad application as shields and filters for thermal neutrons.

Scientists did not restrict themselves to alpha particles

Table VI.

The Half-Lives and Radiations of Some Radioactive Isotopes

Element	Symbol of radioactive isotope	Half-life	Radiation energy in millions of electron-volts	
			Beta Rays	Gamma Rays
Carbon	$_{6}C^{14}$	5720 years	0.155	
Sodium	$_{11}Na^{24}$	15 hours	1.4	1.4; 2.8
Phosphorus	$_{15}P^{32}$	14.3 days	1.69	
Sulphur	$_{16}S^{35}$	87.1 days	0.17	
Chlorine	$_{17}Cl^{36}$	0.4×10^{6} years	0.71	
Argon	$_{18}Ar^{37}$	34.1 days	*K**	
Calcium	$_{20}Ca^{45}$	152 days	0.26	
Scandium	$_{21}Sc^{46}$	85 days	0.36	0.9; 1.12
Titanium	$_{22}Ti^{51}$	72 days	0.45	1.0
Chromium	$_{24}Cr^{51}$	26.5 days	*K*	0.28; 0.32
Iron	$_{26}Fe^{55}$	4 years	*K*	
	$_{26}Fe^{59}$	45.5 days	0.46	1.1; 1.3
Cobalt	$_{27}Co^{60}$	5.3 years	0.3	1.17; 1.33
Zinc	$_{30}Zn^{65}$	250 days	*K*	1.11
Strontium	$_{38}Sr^{89}$	54.5 days	1.46	
Zirconium	$_{40}Zr^{95}$	65 days	0.394; 1.0	0.23; 0.73
Technetium	$_{43}Tc^{99}$	4.7×10^{5} years	0.3	
Silver	$_{47}Ag^{110}$	282 days	0.08; 0.53 2.79	0.11; 0.66; 0.9; 1.4
	$_{47}Ag^{111}$	7.5 days	1.0	
Cadmium	$_{48}Cd^{109}$	330 days	*K*	
	$_{48}Cd^{115}$	43 days	1.85	0.5
Antimony	$_{51}Sb^{125}$	2.7 years	0.3; 0.6	
Iodine	$_{53}J^{131}$	8 days	0.25; 0.60	0.08; 0.36; 0.63
Europium	$_{63}Eu^{155}$	1.7 years	0.18; 0.23	0.084
Hafnium	$_{72}Hf^{181}$	46 days	0.4	0.13; 0.33; 0.47
Tantalum	$_{73}Ta^{182}$	117 days	0.53	1.13; 1.22, etc.
Tungsten	$_{74}W^{185}$	73.2 days	0.43	
Gold	$_{79}Au^{198}$	2.7 days	0.60; 0.96	0.41
	$_{79}Au^{199}$	3.3 days	0.32; 1.01	0.45
Mercury	$_{80}Hg^{205}$	5.5 minutes	1.62	
Thallium	$_{81}Tl^{204}$	2.7 years	0.78	

* *K* signifies *K*-capture, that is, the capture, by the nucleus, of an electron from the *K*-shell of the atom (this process will be discussed in detail in a later chapter).

and neutrons in attempts to obtain radioactive substances. The action of artificially accelerated protons and deuterons was soon the subject of study. The action of a beam of fast deuterons was found particularly effective and resulted in the discovery of many new radioactive substances. It was soon found that there are much larger numbers of new, artificially produced radioactive isotopes than of ordinary stable isotopes. The newly obtained artificial radioactive substances began to find practical applications. They formed the basis of the so-called tracer techniques. Table VI is a list of the characteristics of some of the more important radioactive isotopes.

The remarkable thing is that neutrons, deuterons or protons may be used to obtain radioactive isotopes of any element. This is very important in the practical utilization of radioactive isotopes.

Isomerism of Atomic Nuclei

The study of the interaction of neutrons and nuclei led to the establishment of one more marvellous and important property of atomic nuclei. Credit for this discovery goes to the Soviet physicist I. V. Kurchatov and his pupils. To get an idea of what this is, let us imagine that we have subjected bromine to the action of slow neutrons. What may be expected?

It is a well-known fact that the element bromine consists of two isotopes, Br^{79} and Br^{81}. Since slow neutrons are capable of penetrating atomic nuclei and, after getting stuck there, to form new radioactive nuclei, we may expect the appearance of one or two radioactive isotopes of bromine in accordance with the following transformation schemes:

$$_{35}Br^{79} + {}_0n^1 \longrightarrow {}_{35}Br^{80*},$$
$$_{35}Br^{81} + {}_0n^1 \longrightarrow {}_{35}Br^{82*},$$

that is, resulting from the bombardment of bromine by neutrons one might expect the appearance either of one of two new radioactive substances ($_{35}Br^{80}$ or $_{35}Br^{82}$) or both together, in which case, each of them would have its own half-life (as any other radioactive substance). Of course,

it might happen that the $_{35}Br^{80}$ and $_{35}Br^{82}$ nuclei would turn out to be nonradioactive; in such a case no radioactive substances should be observed. But Kurchatov and his co-workers found that when bromine is irradiated with thermal neutrons there are formed radioactive substances with three half-lives: 18 minutes, 4.4 hours and 34 hours. This means that neutron bombardment of bromine produces three new radioactive isotopes. A series of control experiments showed that all the three half-lives are related to bromine, and, what is more, the bearers of this radioactivity are isotopes of bromine, and consequently they arise from the capture of neutrons by the nuclei of bromine.

Why are three new radioactive isotopes observed when there were only two to begin with? Kurchatov found a correct explanation for these facts. He pointed out that there are actually only two radioactive isotopes formed, and the third half-life corresponds to the disintegration of the nuclei of one of them existing in the *isomeric state*. Recall that isomers are *substances the nuclei of which have one and the same charge (atomic number) and the same mass number, but different energies; so that their half-lives differ.* What Kurchatov established was the formation of isomeric states of the nucleus. More detailed investigations showed that the period of 34 hours corresponds to the decay of the radioactive isotope bromine-82, the half-life of 18 minutes corresponds to the decay of the radioactive isotope bromine-80, and the half-life of 4.4 hours to the decay of nuclei that are isomers of bromine-80.

It was established that the nucleus of the radioactive isomer of bromine-80 has a surplus of energy equal to a mere thirty thousand electron-volts. The isomer of bromine-80 reverts to a normal radioactive bromine isotope by losing this excess energy (it is usually taken up by one of the extranuclear electrons of the bromine atom).

The conversion process of an isomer of bromine-80 into normal bromine-80 does not take place at once, but, just as in ordinary radioactive decay, with a certain probability. This probability is such that during 4.4 hours one half of all the isomeric nuclei convert into nuclei of the normal isotope, which, as we pointed out above, is a radioactive isotope with a half-life of 18 minutes.

It turned out that bromine-80 is not the only substance that has isomers. Subsequent investigations have revealed a large number of such substances.

New Chemical Elements

Nuclear transformations that proceed under the bombardment of different elements with fast particles made it possible to detect many new radioactive isotopes. The number of these isotopes is increasing every single day, and as we have already pointed out, their number exceeds by far that of the stable isotopes. The remarkable thing was that among the new radioactive substances there were found isotopes of hitherto unknown elements.

The Mendeleyev Table, it will be recalled, contains 92 elements. However, not all these elements were in fact discovered. For a long time, elements number 43, 61, 85 and 87 remained unknown. It is true, from time to time reports appeared of the discovery of these elements and of suggested names and chemical symbols for them. But these reports proved erroneous.

Even to this day, no stable isotopes of these elements have been found. Only through nuclear transformations has it been possible to obtain the isotopes of elements No. 43, 61, 85 and 87 and to determine their chemical properties. We even know many isotopes that belong to these elements.

Element No. 43. The isotopes of this element were first obtained by bombarding molybdenum with deuterons accelerated in a cyclotron. To emphasize that this element was first obtained through the use of nuclear techniques, it was given the name "technetium" with the chemical symbol Tc. We already know some ten isotopes of technetium (with mass numbers 92, 94, 95, 96, 97, 98, 99, 100, 101, 102, 105). Four isotopes of technetium (94, 95, 97 and 99) have been found to have isomeric states. The most stable technetium isotope is Tc^{99}. It is beta active and its half-life is 4.7×10^5 years. This isotope (as the most stable one) is at present considered to be the representative of the element technetium. For this reason, the atomic weight of technetium in the Periodic Table is given as 99.

Element No. 61. This element received the name of pro-

methium with the chemical symbol Pm. At present, eight isotopes of this element are known. Only in the case of five has the mass number been established (143, 147, 148, 149 and 151). The most stable isotope has a mass number of 147 and a half-life of 3.7 years.

Element No. 85. This element is called "astatine" and has the chemical symbol At. Ten isotopes are known of this element. Their mass numbers are: 207, 208, 210, 211, 212, 214, 215, 216, 217, 218. The majority of these isotopes are extremely short-lived with half-lives of small fractions of a second, while the half-life of astatine-214 is so small that it has not as yet been measured. Even the stablest of all the known isotopes of astatine (astatine-210) does not live long. Its half-life is only 8.3 hours. It was obtained by bombarding bismuth with alpha particles of energy 29 million electron-volts. The reaction of its formation is as follows:

$$_{83}Bi^{209} + {}_{2}He^{4} \longrightarrow {}_{85}At^{210} + 3 \text{ neutrons.}$$

Astatine-210, being the stablest isotope, is the representative of element No. 85.

Element No. 87. This element is known as francium and has the chemical symbol Fr. A total of five isotopes of francium are known. Their mass numbers are 218, 219, 220, 221 and 223. In the table of the radioactive series of actinium (Table III) the isotope francium-223 is found under the name of "actinium-K." It is obtained in the alpha decay of actinium-227. All the francium isotopes are short-lived. The stablest one has a mass number of 223. But the lifetime of this stablest isotope is not long. It has a half-life of 21 minutes. In disintegrating it radiates beta and gamma rays.

The discovery of elements No. 43, 61, 85 and 87 filled up the empty places in the Periodic Table. However, the study of nuclear transformations has given us much more. The Periodic Table has not only been filled up, it has even been continued. We now have learned of elements No. 93 (neptunium), 94 (plutonium), 95 (americium), 96 (curium), 97 (berkelium), 98 (californium), 99 (einsteinium), 100 (fermium) and 101 (mendelevium) in honour of the eminent Russian scientist D. I. Mendeleyev. We shall describe these elements, their discovery and properties in a later chapter.

Chapter VIII

MESONS

In this chapter we again return to the properties of cosmic rays. It was pointed out earlier that cosmic radiation is complex in composition and that it is common practice to divide cosmic rays into two components: the soft component and the hard component. The soft component of cosmic rays is absorbed comparatively readily by matter, from 5 to 10 cm. of lead being enough to absorb it entirely. The hard component, on the contrary, is very slightly absorbed by matter. A perceptible part of this radiation passes through layers of lead a metre and more in thickness.

What is the cause of this difference in the absorption of these components? The absorption difference could be the result of the different nature of the components. Different rays are naturally absorbed differently. What is more, it is possible in a number of cases to get an idea of the nature of these rays by the type of absorption.

Recall that the complex nature of Becquerel radiation was disclosed due to the different character of absorption of alpha, beta and gamma rays that comprise it.

However, after the experiments of Bothe, Kolhörster, and Skobeltsyn cosmic rays were regarded as a stream of electrons and it was thought that the nature of the two components is the same. It is true that Anderson's discovery modified these views somewhat. It turned out that positrons are also found in the cosmic radiation registered at the earth's surface.

Insofar as it was believed that the hard and soft components of cosmic radiation are of the same type, their different absorption in matter had to be explained by

differences in their energies. To explain the capacity of cosmic electrons to traverse big thicknesses of matter, it was assumed that these electrons (and positrons) possess stupendous kinetic energies. The soft component of cosmic radiation is a flow of electrons and positrons, whose kinetic energy reaches a value of the order of 100 million electron-volts, while the hard component consists of electrons and positrons with energies upwards of one thousand million electron-volts. Incidentally, it should be noted that the sign of the charge of the particles composing the hard component was not established in all cases since these particles are very feebly deflected by a magnetic field.

Ionization and Radiative Losses

An investigation of the movement of particles with high energies (such as electrons and gamma quanta) and their interaction with various substances showed, however, that there was a grave contradiction in such a picture of the cosmic rays.

To explain the essence of this contradiction, recall the phenomena that accompany the movement of electrons and gamma quanta in different substances.

It has long been known that the movement of any particle in any substance results in a loss of energy for the particle. For example, an electron gradually fritters away its energy when moving through air. A careful study of these losses showed that there are two reasons why electrons lose energy.

The first is that when a high-energy electron passes through atoms that it encounters, it interacts with the orbital electrons, which are given a hard knock when they encounter a swift electron. At times it is so strong that one of the electrons is knocked out of the atom, which becomes ionized, the initial electron losing in the act a part of its energy. Moving from atom to atom, it gradually dissipates its energy on the ionization of encountered atoms. This type of energy loss by an electron is known as ionization loss.

We may note some peculiarities relating to the magnitude of ionization losses. The collision conditions of the

electron under study and the extra-nuclear electrons of encountered atoms may differ widely. A so-called "head-on" collision may take place, in which the incident particle moves in a straight line connecting the centres of the interacting particles; an "oblique" collision may occur when the direction of the incident particle forms a certain angle with the straight line connecting the centres of both particles. The amount of energy transferred in different collisions differs. Since the primary electron experiences in its movement a tremendous number of collisions, the most diverse cases may occur. Accordingly, the energy lost by the electron will differ in different collisions. However, in the majority of cases the energy received by an orbital electron is of the order of ionization energy, that is, 20 to 30 electron-volts. Quite naturally such a slight energy loss does not affect the motion of a fast electron with an energy of many millions of electron-volts. Its direction of motion does not change, and continues in a straight line.

A small number of cases are possible when the primary electron (as we shall call the fast electron) communicates to an encountered electron an energy far in excess of what is required to detach it from the atom. In such an event, the dislodged secondary electron will itself possess considerable kinetic energy. It is capable of covering a noticeable distance in air (or in other medium) and on its way it will also ionize atoms that it encounters. The accepted name for these secondary electrons is "*delta rays*." The number of delta rays produced by a primary electron is comparatively small, and therefore the total energy loss due to delta rays is not large.

The principal losses of energy are due to the large number of ionizations in which the electron dislodged from its atom receives a relatively small energy. A high-energy electron makes a large number of such collisions before it fritters away its energy. Since an electron experiences many collisions, there will be among them representatives of various types of collisions. Therefore, although each individual collision has its specific features, on an average, electrons undergoing a large number of collisions lose, due to ionization, approximately the same amount of energy. The energy lost by a fast-moving electron on a section of its path de-

pends of course on its speed, but in addition it also depends on the properties of the medium (such as its density, that is the number of atoms in the path of the moving electron). It is common to characterize the losses by the amount of energy which an electron loses when it traverses a layer of such thickness that in each square centimetre of surface there is one gram of substance. In future, we shall understand by the term *energy loss* the energy lost in traversing a layer of substance of thickness one gram/cm^2.

Ionization losses, as we pointed out, depend on the velocity of the electron. A slow-moving electron interacts with an atom (or with one of its orbital electrons) for a longer time, and therefore imparts to it more momentum, than does a fast electron. For this reason, slow electrons lose energy faster than electrons with a large kinetic energy. In other words, the ionization losses of electrons decrease as the electron energy increases.

However, if the energies are very great (of the order of several million electron-volts) the ionization losses of the electrons will again begin to increase, though slowly. Electrons with a velocity 96 per cent that of light have a minimum loss.

The ionization losses for positrons are analogous.

Ionization losses resulting from the interaction of a particle with the bound electrons of an atom are only one type of energy loss for fast electrons. Besides ionization losses there are known to exist so-called radiative losses.

The essence of radiative losses is this: when an electron comes close to a nucleus, there is interaction between it and the nucleus. This interaction is much stronger than that of the electron and an orbital electron because the charge of the nucleus is considerably greater than that of an electron. Due to the big mass of the nucleus and the strong interaction, the incident electron is sharply decelerated. In this act the electron loses a substantial part of its energy, which is released in the form of a quantum of electromagnetic radiation (a photon). The greater the energy of the electron the greater is the part lost in deceleration and the greater is the energy of the photon emitted by the electron.

However, the probability of photon emission is not very great, since a photon is emitted only when the electron

passes sufficiently close to the nucleus, and the nucleus, as we already know, occupies a very small part of the volume of the whole atom. Photons are emitted so rarely that although considerable energy is lost by the electron when the event occurs, the average energy losses due to radiation (radiative losses) by electrons of not very high energies are small in comparison with ionization losses. On the basis of these data experimentally verified for electrons of comparatively small energies, the conclusion was drawn that the energy losses of electrons are principally ionization losses, and since ionization losses diminish with increasing electron energy, then, consequently, as the energy increases, the electron range (the path covered by an electron until it comes to rest, or, more precisely, until the energy of the electron has become so small that it is no longer capable of ionizing the atoms it encounters) will also increase. If electron energy losses did not depend on the velocities of the particles, their ranges would increase as many times as their energy. Actually, however, the electron range varies with increasing energy according to a more complex law. At the beginning, an energy increase produces a very rapid increase in range; this is due to two causes operating at once: *increase* in electron energy and *decrease* in losses (the energy lost per unit path). Subsequently, however, when the electron energy reaches a value of several million electron-volts, the range increase with electron energy is slower. In this case, ionization losses begin to increase but slightly with the energy. Since this growth of ionization losses is insignificant, the range of an electron even in the case of very high energies should still increase perceptibly (almost linearly) with the energy. If we calculate (on the basis of the known values of energy loss) what energy an electron should possess in order to be able to pass through one metre of lead without losing it entirely on ionization, we find it to be of the order of several thousand million electron-volts.

It was precisely for this reason that the assumption was made that those particles in the cosmic radiation which are capable of passing through considerable thicknesses of matter (the hard component) are electrons of stupendous energies expressible in the thousands of millions of electron-volts.

In order to give the reader a more accurate picture of ionization losses of energy, we give in Fig. 40 curves *I* that represent ionization losses in water and lead as a function of electron energy.

However, Bethe and Heitler, who made a detailed theoretical investigation of the problem of radiative losses,

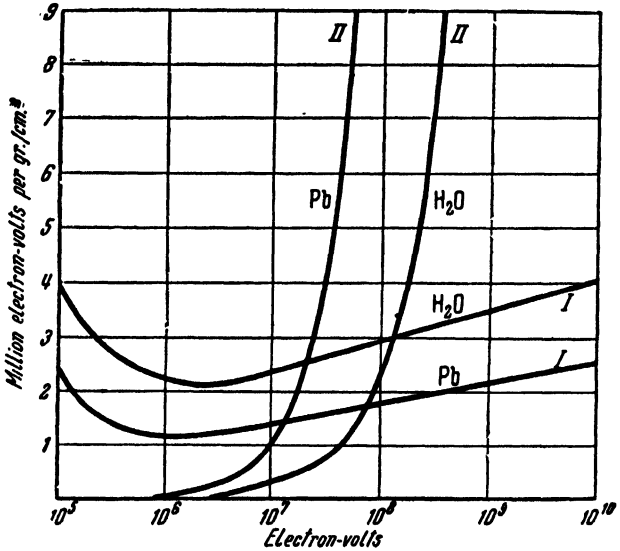


Fig. 40. The dependence of ionization and radiative losses on electron energy. Curves *I* are the ionization losses in lead and water. Curves *II* are the radiative losses in the same substances. In water the radiative losses begin to surpass the ionization losses at electron energy of the order of 100 million electron-volts, while in lead it occurs at an energy of the order of 10 million electron-volts.

showed that these losses grow with the energy of the electron considerably faster than do ionization losses, and at sufficiently high electron energies they not only become comparable to ionization losses, but even exceed them appreciably so that electrons of such energy lose energy principally by radiation.

The ratio between ionization and radiative losses is different for different substances. The greater the charge of the nucleus, the bigger the part played by radiative losses. Fig. 40

also shows curves *II* that express, according to the computations of Bethe and Heitler, radiative losses of electrons in water and lead as a function of energy.

The Bethe-Heitler calculations show, for example, that electrons of energy greater than 100 million electron-volts lose energy chiefly by radiation, and not by ionization; and the increase in radiative losses with increasing electron energy is so great that an electron cannot have a range in air over 300 metres, because no matter what energy the electron may have it will have lost a substantial part of it by radiation. The greater the energy of the electron, the faster it loses energy by emitting high-energy photons.

The conclusions of the Bethe-Heitler theory were confirmed experimentally by many workers, including the Soviet scientists Alikhanov and Alikhanyan, Artsimovich, Sinelnikov, Korsunsky and Valter.

Confirmation of the Bethe-Heitler theory had far-reaching consequences for the development of our knowledge of cosmic rays. It focussed the attention of scientists on the question of the nature of the hard component of cosmic radiation.

On this theory, no matter how great the energy of the electron or positron it is not able to pass through a one-metre layer of lead. Suppose there really do exist electrons and positrons with energies of the order of 10^9 or even 10^{10} electron-volts in cosmic radiation. Let us see what fate has in store for them.

Let an electron be moving in air. Then, according to Bethe and Heitler, within a distance of 300 metres it will have lost its energy in the form of a gamma quantum. We may simplify the actual situation by agreeing that the energy of the quantum produced is equal to the entire initial energy of the electron. The direction of motion of the quantum will practically coincide with the original direction of motion of the electron. The electron will apparently have converted into a gamma quantum*.

Now what will happen?

How does a gamma quantum of such energy behave?

How does it interact with matter?

* Of course, the electron does not disappear after having emitted a gamma-ray quantum, but its energy is so small that it is no longer able to participate in the processes under consideration.

Showers

In Chapter V we related how the formation of a positron by high-energy gamma-ray quanta was discovered. It was pointed out that beginning with an energy of one million electron-volts, there occur anomalies in the dependence of gamma-ray absorption on energy: there appears an additional absorption of gamma rays due to electron-positron pair formation. The probability of pair production by gamma rays increases with the energy of the gamma quanta, and at very high energies gamma-quanta absorption will be almost entirely due to pair formation. This means that a high-energy gamma quantum (photon) interacting with matter is converted into two particles—an electron-positron pair. The energy of each of these particles will, on the average, be equal to one-half the energy of the photon. Although the direction of motion of these particles does not coincide with the direction of motion of the photon, it is sufficiently close.

Here is what happens. A high-energy electron (and positron as well) emits a gamma quantum of approximately the same energy and moving in practically the same direction as the electron. In its turn, the photon converts into two particles moving in approximately the same direction but each with half the energy. These new particles share the fate of the primary electron: within about 300 metres of air they create photons.

Each of these two photons produce, in their turn, a pair of particles. Now there will be four particles in motion.

It is not difficult to imagine what follows. After covering another several hundred metres, these four particles will turn into eight particles, then sixteen, then thirty-two, and maybe up to sixty-four, and more.

Thus what happens during the motion of a fast electron is multiplication of particles, which can be nicely visualized in Fig. 41. As the electrons and positrons (and also photons) multiply, their energy diminishes. The multiplication process will continue until the electron energy reaches a value at which ionization losses begin to exceed radiative losses. Then the interaction of electrons and positrons with matter will no longer lead to the formation of new photons. In the

air, multiplication ceases when the energy of the electrons reaches several tens of millions of electron-volts.

The number of particles produced in the process of multiplication will depend on the original energy of the electrons. The greater the energy, the larger the number of particles produced by the electron.

Thus the theory predicts that electrons of energy of several or even hundreds of thousands of millions of electron-

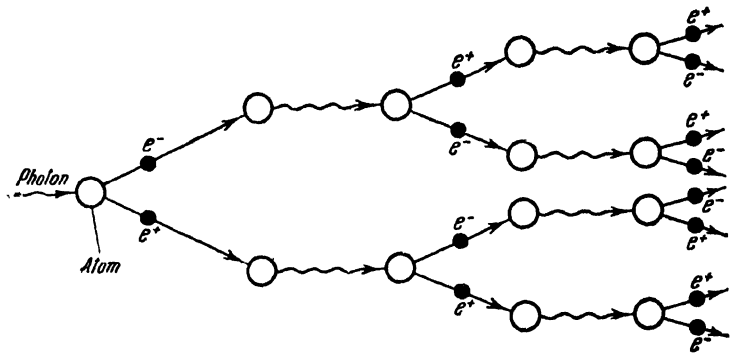


Fig. 41. Diagram showing the formation of a cosmic shower.

volts are not able to penetrate our atmosphere. On the way they produce a large number of particles, which collectively are known as a "shower."

The energy of the electrons and positrons making up the shower is not very great. It of course depends on how developed the shower is, because, as we have already pointed out, the development of a shower continues until the energy of the particles has become of the order of several tens of millions of electron-volts. Electrons of this energy are relatively quickly slowed down in the atmosphere.

However, if the energy of the primary electron proves greater than 10^{13} electron-volts, the shower produced by this electron is able to reach the earth's surface (sea level). Obviously, such a shower will be composed of a huge number of electrons and the shower itself will cover a large area. The shower extends as the particles in it multiply because the positrons and electrons produced during the absorption

of photons do not move in exactly the direction of the quantum, but at a definite, though small, angle to it. In consequence, the shower spreads out as it develops. Big showers extend over areas of several tens of thousands of square metres. The French physicist Auger using a system of counters separated by distances of several tens and even hundreds of metres, detected showers covering areas of over 10,000 square metres. From the number of electrons comprising such a shower, Auger calculated that the primary particle which caused the shower should have an energy expressible by the truly astronomical figure of 10^{16} (10,000 million million) electron-volts.

The above-described picture of shower production was also observed in a cloud chamber. These observations were possible because the process of shower formation, which in air drags out into hundreds of metres, takes place in relatively small distances in lead. From the curves in Fig. 40 it is seen that whereas in water (and also in air) the radiative losses exceed the ionization losses only at electron energies above 100 million electron-volts, in lead already at energies of 10 million electron-volts the radiative losses begin to predominate over ionization losses. Besides, due to the great density of lead, energy losses in it per unit of path are many times greater than the losses in air (one gram of matter per square centimetre corresponds to a layer of lead slightly less than 1 mm., and a layer of air about 10 metres in thickness). A consequence is the more rapid development of showers in lead, where it shows a marked development even in a one-centimetre plate. In addition, shower development in lead continues to much smaller electron energies.

Cloud-chamber pictures taken when the chamber is crossed by several layers of lead (Figs. XXVII and XXVIII in the Appendix) give a clear picture of shower development. Fig. XXIX (see Appendix) exhibits a shower produced by a very high-energy electron; the tracks of the shower particles fill up the entire chamber. These pictures serve as a good illustration of the correctness of the Bethe-Heitler theory and the so-called cascade theory of showers based on it and developed in large measure by L. D. Landau, I. E. Tamm, and S. Z. Belenky. A study of the absorption of shower particles showed that in general outline it is similar to the absorption of the soft component of cosmic rays. The nature of

the soft component of cosmic rays has been clarified by the shower theory. But the nature of the hard component has become still more puzzling.

Indeed, it was believed earlier that single particles passing through a considerable thickness of lead and not deflected in a magnetic field were electrons or positrons with high kinetic energy. This hypothesis now had to be discarded. High-energy electrons and positrons must form showers. Insofar as we observe the track of a single particle, the latter cannot be either an electron or a positron. Nor can it be a photon. Then what is this hard component of the cosmic radiation?

The Discovery of the Meson

While studying the nature of the nuclear forces that hold together the particles of atomic nuclei, Yukawa came to the conclusion in 1935 that in order to give a proper description of the character of these forces it is necessary to hypothesize the existence of particles whose mass is intermediate between the mass of the proton and that of the electron. In Yukawa's opinion such particles should possess a mass some 100 to 200 times that of the electron.

When it was found that the particles comprising the hard component of cosmic radiation can be neither electrons nor positrons, nor photons, the natural thing to suppose was that possibly the Yukawa particles ("heavy electrons" of 200 electronic masses) actually exist in nature and make up the hard component of the cosmic radiation.

And true enough, the properties of such "heavy electrons" resemble the properties of the hard component of cosmic radiation. It is known that radiative losses are a function of the mass of the particle. In describing the betatron we pointed out that radiative losses diminish in inverse proportion to the fourth power of the mass of the charged particle. Consequently, the "heavy electron" of 200 electronic masses will experience radiative losses one thousand million times less than an ordinary electron of the same energy. Radiative losses of heavy electrons will be so small, that their magnitude (if compared with ionization losses) may be ignored and it may be considered that a "heavy elec-

tron" in passing through matter loses energy only through ionization of the molecules of the substance. Since at high velocities ionization losses are small, a heavy electron of high energy is capable of traversing big thicknesses of matter. Inasmuch as the "heavy electron" does not experience radiative losses, it will not create showers. Thus, we see that there is a similarity between the behaviour of particles comprising the hard component of cosmic radiation, and the behaviour of the hypothetical "heavy electrons."

To confirm this hypothesis, it was necessary to measure the mass of such a particle and to be sure that it was actually 200 electron masses. The experimental data corroborating this hypothesis were first obtained by Anderson and Neddermeyer. They observed the passage of cosmic rays through a lead plate in a cloud chamber and measured their energy.

How was it possible by means of such observations to establish that the masses of these particles differ from that of an electron? It wasn't very easy, but still it was possible. And what is more, it was found possible to determine the mass of such particles. There are several magnitudes that characterize the mass of a particle. One is the range. The greater the mass of a particle, the less is its speed (for a given energy); and the less the speed of a particle, the greater will be the ionization losses and the shorter the path traversed by the particle in matter.

However, the range depends not only on the mass, it is also a function of the speed of the particle. So the range alone is not enough to give the mass. Besides, it is not always possible to determine the range experimentally. For example, to determine the range of a particle in a cloud chamber, it is necessary that the path of the particle should not go beyond the chamber. Obviously, only when the energy of the particle is not great, that is when the particle has a range that does not exceed the limits of the chamber, can this range be measured. But if the range is small the energy of the particle will likewise be small. In short, the range of a particle may be used to measure its mass only in the case of low-energy particles.

It is of course possible to determine the mass of a particle by its deflection in a magnetic field. But in this case also,

as may be seen from equation (2) (p. 21), we determine, properly speaking, not the mass but the momentum of the particle which is a function both of the mass and the speed. This method is indirect, too. Besides, due to the limited magnitude of the intensity of the magnetic field, it is suitable for energies that are not too big.

The ionizing power of the particle may also be taken into account. The ionizing power is characterized by the number of ion pairs produced by a particle per unit path traversed. Properly speaking, the ionizing power of a particle is determined not by its mass but by its speed. The greater the speed, the less the ionizing power. However, by correlating data on the ionizing power of a particle with other information, such as the range or the radius of curvature of its trajectory in a magnetic field, it is possible to determine the mass of the particle. It is relatively easy to obtain information about the ionizing power of a particle. One way is by means of a cloud chamber, another, with a photographic plate. These two methods are most frequently used to determine the mass of a particle. An illustration of the ionizing power of different particles is seen in Fig. XXX (see Appendix).

And finally, some idea about the mass of a particle may be gained by energy losses in lead plates. These losses are a function both of the energy of the particle and its mass. By combining the results of these measurements with the ionizing power of the particle, and in certain cases with the curvature of its path in a magnetic field, it is possible to determine the mass of the particle. This is exactly what Anderson and Neddermeyer did.

While checking the applicability of the Bethe-Heitler equation to energy losses of cosmic rays in lead, they detected in a cloud chamber the tracks of particles that had lost considerably less energy in passing through a lead plate in the chamber than did electrons. A correlation of the ionizing power of these particles and their energy loss in a plate of lead of given thickness gave them the mass of the particles. It should be pointed out that this method of determining the mass is not very exact, giving only a general idea about the mass of the particle. According to the data of Anderson and Neddermeyer it appeared that the mass of the particle under

investigation is intermediate between that of an electron and that of a proton and that the most probable value is between 100 and 200 electron masses.

Fig. XXXI in the Appendix is a picture taken by Anderson and Neddermeyer. It shows the track of a particle that passed through a Geiger-Müller counter placed in a cloud chamber. The mass of this particle was computed to be 220 electron masses. As we have already pointed out, the error in such a calculation may be substantial, and the true value of the mass may be slightly greater or less than this figure; however, it is doubtless that the particle whose track is shown in Fig. XXXI has a mass intermediate between that of an electron and a proton. The conclusions of Anderson and Neddermeyer were soon confirmed in the experiments of other workers. That was how this new particle, the meson (which means "intermediate," that is, between the mass of an electron and a proton) was found.

The Lifetime of a Meson

The discovery of the meson was an outstanding event that extended the list of elementary particles. It shed new light on the problem of the nature of cosmic radiation. It was also found that mesons play an important part in the interaction of nuclear particles. This was the reason why an intensive study of the newly discovered particles began.

Already the first observations with cloud chambers placed in magnetic fields showed that there are mesons charged positively and negatively. The magnitude of the meson charge has not been measured directly; from indirect data however, it is found to be equal to that of an electron. Rather recently (1948-50), proof was obtained of the existence of mesons without any electric charge, neutral mesons.

Mesons turned out to be unstable particles. They live only a short time and then decay. The decay time of a meson depends on its energy. A slow meson has a half-life of 2.15×10^{-6} sec.

When a meson decays, the energy associated with its mass is converted into the kinetic energy of other, lighter particles that arise from the decay. This is what underlies

the method of measuring the half-lives of mesons. To make the essence of this method clear, the reader's attention is directed to a procedure used at present to determine the direction of motion of high-energy ionizing particles.

Picture three Geiger-Müller counters A, B, and C (Fig. 42) arranged so that their axes are parallel. If a single ionizing particle passes through all three counters, there will be a discharge in each one of them. The instant of discharge in each counter will differ by a lapse of time required for the particle to cover the distance between the counters. Since the speed of high-energy particles is close to that of light, and the distance between the counters is only several tens of centimetres, this time will be of the order of 10^{-9} sec. It is so small that the origin of discharges in all three counters may be considered as simultaneous. Let us connect all these counters in coincidence. This means that the electronic circuit that amplifies the pulses produced during discharges in the Geiger-Müller counters is connected in such a way that it records only cases when there is a simultaneous discharge in all three counters. If, for example, there is a discharge in two of the counters, and none in the third, then such cases will not be recorded when the counters are connected in coincidence. Therefore, if the coincidence circuit is triggered this means that discharges have occurred in all three counters, that is, in other words, that the ionizing particle has passed through all three counters. The position of the counters is what determines the path of the particle. Possible trajectories of such a particle are shown in Fig. 42. Such a group of counters designed to determine the direction of motion of a cosmic particle is called a telescope.

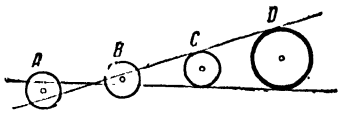


Fig. 42.

A telescope may be used to establish not only the path of the particle (the direction of its motion), but also to determine whether the particle underwent transformation over this distance. To do this, a fourth counter D (connected in anticoincidence) is added to the counters A, B, and C connected in coincidence. An anticoincidence circuit is one in which the amplifying valves are so connected that the

last stage of the circuit is triggered only when discharges occur in the three counters connected in coincidence, while in the fourth, supplementary counter, D, there is no discharge. If a simultaneous discharge occurs in all four counters, that is, if an ionizing particle passes through all the counters, the anticoincidence circuit will not respond. Consequently, such a circuit registers only such cases when the ionizing particle passes through counters A, B, and C, but disappears between counter C and counter D; using such a system of counters, it is possible to determine the half-life of a meson.

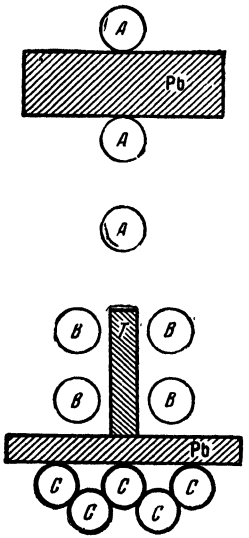


Fig. 43. Experimental arrangement for determining the "lifetimes" of cosmic-ray mesons.

An experimental arrangement to determine the half-life of a meson is shown in Fig. 43. Here, the three counters A register the direction of the flying particle. They are connected in coincidence. To separate the electrons and positrons from the mesons, a 10-cm. layer of lead (enough to absorb the soft component) is interposed between the first and second counters. The electrons and positrons are not able to pass through all the A counters; therefore a simultaneous discharge in these counters can occur only when a meson passes through the counters (and the lead). After passing through the three A counters, the meson enters a lead filter, T. In this filter, some of the mesons are slowed down completely and some (depending upon their initial energy) are capable of going further. To select those cases when the mesons are completely stopped in the filter T, a number of Geiger-Müller counters C are placed under the filter. The C counters are arranged so that any meson that has traversed the T filter will pass through one of the C counters. Counters A and C are connected in anticoincidence, that is, the electronic circuit registers only cases when the

meson has passed through all the A counters but has not passed through a single one of the C counters. Obviously, this will occur only when the meson has been stopped in the substance of the filter T.

This meson, as we already know, will decay and produce an electron with an energy of the order of 100 million electron-volts. It is the job of counters B along each side of filter T to catch such electrons. However, since the meson does not decay instantaneously, the electrons will enter counters B slightly after counters C and A have been tripped. For this reason, the electronic circuit was arranged so that the discharges in counters B were recorded with a certain given lag with respect to counters C and A. By varying the time lag and measuring the number of particles registered by counters B, it is possible to determine the meson decay rate. As we have already stated above, the half-life of a meson was found to be 2.15×10^{-6} sec.

Mesons make up the hard component of cosmic radiation. At sea-level 70 per cent of the cosmic radiation is comprised of mesons. High-energy mesons are capable of traversing considerable thicknesses of lead. However, they are unable to cover a big distance in air because their lifetime is so short. For this reason, mesons cannot be a component part of the primary cosmic radiation coming to earth from cosmic space. They are secondary formations created in the earth's atmosphere.

The Mass of Mesons

An interesting method of determining the mass of mesons was developed by a group of Soviet scientists headed by A. I. Alikhanov and A. I. Alikhanyan.

In 1943-45, this group of workers organized a permanent station for cosmic radiation studies on Mt. Alagyoz at an altitude of 3,250 m. Work at this station is still in progress. A special permanent magnet to create a strong magnetic field in a large volume (with an interpole gap of 8 cm. $\times$ 12 cm. $\times$ 50 cm. and a field intensity of 3,840 oersted) was carried to this height. The magnet poles were rectangular in cross-section with sides of 50 cm. $\times$ 12 cm. The magnet

was set up with the 50-cm. side of the rectangle standing vertical. This was done so that the incoming cosmic particles would cover the greatest possible distance in the magnetic field. This magnet was used to study the deflection of mesons in a magnetic field. The magnitude of the deflection made it possible to determine the meson mass.

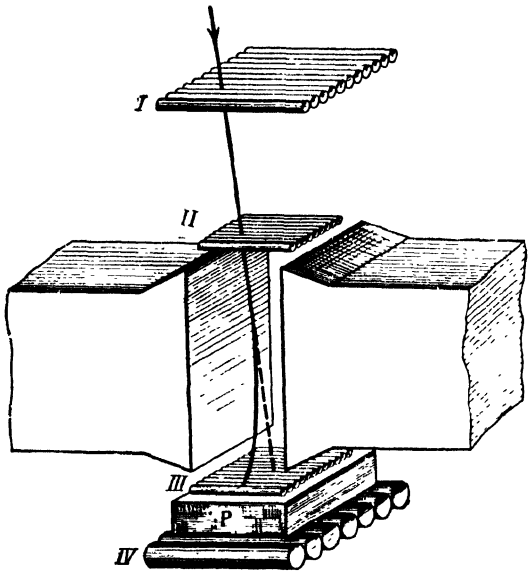


Fig. 44. Layout of the Alikhanov-Alikhanyan experiments for determining the masses of cosmic-ray particles.

The layout shown in Fig. 44 was used to measure the magnitude of deflection of mesons. Three rows of counters (*I*, *II* and *III*) map out the path of the particle. The first two rows of counters above the poles of the magnet are designed to determine the path of the particle before its entry into the magnetic field, the third row of counters records any change in the motion of the particle over the 50-cm. path that it covers in the 3,840-oersted magnetic field. The path of the particle is determined in the following manner: each one of the Geiger-Müller counters in these three rows

is connected with a neon lamp which flashes when an ionizing particle passes through it.

These three groups of counters are connected in coincidence, that is, the circuit registers only cases when the particle passes through counters in all three rows. A motion-picture machine is then actuated to record on film the three neon lamps that flash. By determining which of the counters in rows *I*, *II* and *III* are tripped we find out the deflection the particle experienced when passing through the magnetic field.

The axes of the counters were set in the direction of the lines of force of the magnetic field, that is, perpendicularly to the poles of the magnet. The magnetic field is directed parallel to the plane of the drawing.

However, by itself the deflection of a particle in a magnetic field is not enough to determine its mass.

As has already been pointed out, the deflection of a charged particle in a magnetic field determines not its mass but its momentum, that is, the product of the mass and velocity.

To get an idea of the speed of particles, a study was made of particle absorption in lead. For this purpose, a 5.4-cm. thick lead block *P* was placed under the third row of counters. Under this block was a fourth row (*IV*) of counters connected in anticoincidence with the first three rows. This connection of the fourth row of counters in anticoincidence with the first three means that the electronic circuit that actuates the motion-picture machine is triggered only when a particle passes through certain counters in each one of the first three rows but does not pass through a single counter of row *IV*.

Thus, the photographs obtained of neon-lamp flashes register only those cases when a particle passes through three rows of counters and then gets stuck in the lead block.

However, three rows of counters were found to be insufficient to give a reliable determination of the trajectory of a particle, and in subsequent experiments the number of rows was increased to five. The magnetic field was also increased. In the process of investigations a rather large number of cases were found when particles that were but feebly deflected by the magnetic field were absorbed in the lead filter. If such particles had a mass of 200 electron masses

(the supposed mass of the meson), then slight deflection in a magnetic field would have meant that they possessed a huge energy, sufficient at any rate to push them through a layer of lead 5.4 cm. in thickness. But in a layer of lead of this thickness, the particles are completely slowed down. The only explanation is that the mass of the particle at hand is more than 200 electron masses. Indeed, the greater the mass of a particle (for a given momentum) the less its speed and energy and the more strongly the particle is decelerated in a lead filter.

The very first results of the Alikhanov-Alikhanyan investigations showed that among the particles passing between the poles of the magnet there were not only 200 electron-mass mesons but also other particles with a mass intermediate between 200 electron masses and the mass of a proton. Subsequently, after refining their apparatus, they found particles with masses close to 300, 600 and 900 electron masses.

Still more interesting information about mesons was obtained by means of thick photographic emulsions. If we take plates with a fine-grain emulsion, it is possible (from the nature of the track) to distinguish particles of different ionizing power. The greater the ionizing power of a particle, the more blackened grains of the emulsion are detected along its path when the plate is developed. The number of blackened grains per unit length of path of the particle is an indication of the ionizing power, and hence also the speed of the particle. Thus one can get an idea of the speed of a particle from its track in a photographic emulsion just as in a cloud chamber.

Registration of tracks in emulsions has many advantages. A photographic emulsion can record the range of particles of much greater energies than can a cloud chamber. The density of emulsion is approximately 2,000 times that of air, and so a particle that covers 10 cm. in a cloud chamber will cover only 50 microns in a photographic emulsion. Modern emulsion photographic plates have thicknesses of several millimetres. In such plates (if the layer of emulsion is in a vertical position), a particle can cover a distance up to 10 centimetres. The same particle would traverse roughly 200 metres in a cloud chamber.

The possibility of measuring the ranges of high-energy particles is an essential advantage of the photographic emulsion method. Another advantage of no small significance is that a stack of photographic plates may be exposed to cosmic rays during a period of time long enough to record on a single plate (or to be more exact in one stack of plates) a large number of the most diverse cases of cosmic-particle interaction. For this reason, photographic plates are especially convenient for recording rare processes; it has been possible to observe in them certain details of the transformation of particles which usually escape the worker in cloud chambers.

In 1947, Powell and Occhialini published the results of their remarkable investigations of tracks of cosmic particles in thick photographic emulsions. On some of the pictures (one of which is shown in Fig. XXXII in the Appendix) obtained by these workers, we can see the end of the path of a particle (In Fig. XXXII this particle is marked π). The track this particle left in the emulsion of the photographic plate is very long, much greater than the field of view of the microscope in which the track is examined. And so a whole patchwork of a large number of microphotographs had to be built up so as to get a full picture of this track.

The position of the blackened grains of the emulsion, or to be more exact, the number of these grains produced per unit length of path determines the speed of the particle, and the length of the track determines its energy. The data on the energy in conjunction with the known magnitude of the speed permit of determining the mass of the particle. It was found to be roughly 300 electron masses.

It is easy to determine the direction of motion of the particle. A moving particle gradually loses its energy, and its speed; and, as we know, the ionizing power of the particle increases as the speed diminishes. The higher the ionizing power, the greater will be the number of blackened grains. Consequently, the motion of a particle that has left a track in the emulsion occurs from the point where the density of blackened grains is small to the point where it is greatest. The end of the range is characterized by maximum density of the blackened grains.

In this picture we see that at point A (the end of the range of a particle of mass 300 m_e, where m_e is the rest mass of an electron) there appeared a new particle, the whole range of which was on this same photographic plate. In Fig. XXXII, this particle is labelled μ. A measurement of the range of this particle and also of its ionizing power (from the number of blackened grains) made it possible to determine its mass, which turned out to be approximately 200 m_e. Thus, Fig. XXXII illustrates the transformation of a particle of mass 300 m_e into another particle of mass about 200m_e.

On the basis of these data, and also of the results of investigations of similar pictures, Powell and Occhialini drew the conclusion that in addition to mesons of mass close to 200 m_e there must be mesons with a mass roughly equal to 300 m_e. They called mesons of mass 200 m_e mu-mesons (μ), and those of mass 300 m_e pi-mesons (π).

In 1947, mesons were obtained artificially by bombarding beryllium, carbon, copper and uranium with alpha particles accelerated in a synchrocyclotron to an energy of over 300 million electron-volts. The number of mesons observed increased with the energy of the alpha particles. By the deflection of these mesons in a magnetic field and by their range it was possible to determine both the sign of the meson charge and its mass.

It was found that there exist pi-mesons of positive and negative charge. The mass of both pi-mesons was the same, 276 m_e. Mu-mesons of both signs also occur. Their mass is 212 m_e.

In addition to the charged pi-mesons, neutral pi-mesons* were also discovered. Since these particles have no charge they do not ionize matter and therefore do not leave a track in photographic emulsions. Their existence was hypothesized on the basis of indirect data, by the appearance of gamma quanta (of energy of the order of 100 million electron-volts) into which the neutral pi-meson decays.

The mass of a neutral pi-meson deduced from data on the energy of gamma quanta proved slightly less than the mass of a charged pi-meson, or 264 m_e. The neutral pi-meson has a lifetime of only 3×10^{-14} sec.

* Neutral pi-mesons are designated by π^0 to distinguish them from the chagred mesons π^+ and π^-.

Nuclear Transformations Produced by Pi-Mesons and the Transformation of Pi- and Mu-Mesons

While studying the tracks of pi-mesons in emulsions, Powell and Occhialini noticed many cases where the pi-mesons penetrated into atomic nuclei of the emulsion and destroyed them. Fig. XXXIII in the Appendix shows photographs of such transformations.

A pi-meson enters a nucleus carrying with it a tremendous energy. It is due to this energy that many particles (protons, neutrons, alpha particles) leave the nucleus. In the process, such light nuclei as those of carbon, nitrogen, oxygen can completely break up into separate particles. Such nuclei seem to explode. The particles produced in the explosion may be observed by the tracks they leave in the emulsion. Fig. XXXIII shows how pi-mesons destroyed just such light nuclei. Each picture shows the tracks of three or four particles produced by an explosion. The track of the pi-meson stops at the point of the explosion. The pi-meson is obviously absorbed by the nucleus.

At first glance it may seem that there are too few particles in the photographs, since there are twelve particles in a carbon nucleus and sixteen in a nucleus of oxygen. But recall that not all the particles in a nucleus are capable of ionizing. Neutrons, being neutral particles, do not ionize and therefore their tracks in the emulsion are not visible. There are considerably fewer charged particles (protons, alpha particles) capable of producing ionization. A carbon nucleus has six protons and an oxygen nucleus eight. However, the disintegration of a nucleus is not always attended by the ejection of protons; alpha particles containing, as we know, two protons and two neutrons, are sometimes observed. The ejection of alpha particles reduces the possible visible number of particles. For example, if only alpha particles were ejected in the decay of a nucleus, we should observe only three particles in the decay of a carbon nucleus and only four particles in the decay of an oxygen nucleus. In actuality, protons and alpha particles and neutrons are ejected.

The pictures we examined and also a large number of others show that pi-mesons are *nuclear-active particles.*

This term emphasizes the ability of pi-mesons to interact actively with atomic nuclei and, on encountering a nucleus, to excite its transformation at the expense of the huge energy imparted to the nucleus.

Both fast and slow pi-mesons accomplish nuclear transformations, but they do it differently. Negative pi-mesons cause nuclear transformations considerably more often than do positives. The reason for this difference is easy enough to understand. The charge of the nucleus is positive. Therefore mesons with a negative charge are attracted by it. Negative mesons do not need to have a big kinetic energy to penetrate into a nucleus. For this reason, even slow negative mesons can enter a nucleus and transfer to it the energy of the mass of the meson. Positively charged mesons are repelled by the nucleus, and so must possess a huge kinetic energy to overcome the repulsion and penetrate into the nucleus. This difference in the interaction of mesons with nuclei is the reason why nuclei are more often disrupted by negative pi-mesons than by positives.

The nuclear activity of pi-mesons is manifested not only in their ability to produce nuclear transformations; pi-mesons themselves frequently appear as a result of the destruction of heavy and light nuclei by cosmic particles (protons, alpha particles). Fig. XXXIV shows the explosion of a nucleus produced by a cosmic particle. It shows not only the tracks of heavy particles, but also of pi-mesons produced in the explosion of the nucleus.

The properties of mu-mesons differ essentially from those of pi-mesons. Mu-mesons proved to be particles that do not interact with atomic nuclei at all, or that interact with them very feebly.

Pi-mesons have frequently been observed in nuclear explosions produced by cosmic particles, but mu-mesons are not found to appear. At present, nuclei are disrupted by high-energy protons and alpha particles in the laboratory. Pi-mesons are frequently found among the particles produced in this process, but there are no mu-mesons. There likewise have been no cases of nuclei being destroyed by mu-mesons. Mu-mesons turned out to be *nuclear-inactive particles*.

In this connection it is curious to note that the idea of the possible existence of mesons was first advanced in the

search for an explanation of the nature of nuclear forces. As has been pointed out, Yukawa believed nuclear interactions to be due to particles of mass 100 to 200 m_e. The discovery of mu-mesons in cosmic radiation at sea-level seemed to corroborate Yukawa's hypothesis since the mass of these mesons was close to 200 m_e. However, a correlation of the properties of pi- and mu-mesons shows that the pi-mesons are nuclear active and that, consequently, the nuclear forces are due to the action of pi-mesons and not mu-mesons.

If mu-mesons are not nuclear-active particles and do not originate in the disruption of atomic nuclei, how is one to explain the fact that it is precisely these mesons that are predominant in secondary cosmic radiation near the earth's surface and at small altitudes. Where and how are they produced?

Let us return again to Fig. XXXII, which is incontestable proof of the transformation of a pi-meson into a mu-meson. It follows that mu-mesons arise out of the decay of pi-mesons. At high altitudes, pi-mesons are predominant, originating from the destruction of nuclei by primary cosmic particles. But pi-mesons are very short-lived and do not succeed in reaching the earth's surface.

The transformation of pi-mesons into mu-mesons is accompanied by the appearance of neutral particles (apparently, the so-called neutrinos which will be discussed later on). Since no other charged particles with the exception of a mu-meson are observed in the decay of a pi-meson, we may regard the pi-meson decay as proceeding according to the following scheme:

$$\pi^+ \longrightarrow \mu^+ + \nu,$$
$$\pi^- \longrightarrow \mu^- + \nu$$

that is, a positively charged pi-meson converts into a positively charged mu-meson, and a negative mu-meson originates from a negative pi-meson. The letter ν denotes a neutral particle (neutrino).

The mean lifetime of a pi-meson was found to be 2.6×10^{-8} sec., which is nearly 100 times less than the mean lifetime of a mu-meson.

The decay of a mu-meson produces an electron or positron, depending on the sign of the charge of the mu-meson, and two neutral particles (neutrinos)

$$\mu^+ \longrightarrow e^+ + 2\nu,$$
$$\mu^- \longrightarrow e^- + 2\nu.$$

The result is a long chain of transformations

$$\text{nucleus} \longrightarrow \pi^{\pm} \longrightarrow \mu^{\pm} \longrightarrow e^{\pm}.$$

The last three links of this chain ($\pi \rightarrow \mu \rightarrow e$ = decay) have been recorded in a number of emulsion photographs (see Appendix, Fig. XXXV).

Heavy Mesons

The investigations of Powell and Occhialini, Alikhanov and Alikhanyan, and many others have shown that in addition to the pi- and mu-mesons, there exist other, heavier mesons and also particles of mass intermediate between that of a proton and a deuteron. All these particles are unstable. They decay after a very short lifetime into other familiar particles such as pi- and mu-mesons, electrons and positrons. It is from the tracks of these transformations that such mesons are detected and their properties and mass determined.

At present, we may regard as established the existence of mesons possessing the following values of mass:

a) *Mesons of mass close to 500 m_e.* The mass of these mesons has not been established very accurately. According to Alikhanyan's data, these mesons are nuclear inactive just as mu-mesons. Among the particles that originate in nuclear explosions, mesons of mass 500 m_e are not observed. They are apparently the decay product of heavier mesons.

b) *Theta-mesons* (θ^0-and $\theta^{\pm}$-mesons). These are neutral and charged mesons of mass close to 800 m_e that decay according to the schemes:

$$\theta^0 \longrightarrow \pi^+ + \pi^-,$$
$$\theta^{\pm} \longrightarrow \pi^{\pm} + \pi^0.$$

The mean lifetime of a neutral theta-meson is of the order

of 1.7×10^{-10} sec. It has not yet been possible to measure the mean lifetime of $\theta^{\pm}$-mesons.

c) *K-mesons* are charged mesons of mass close to 1,250 m_e that decay according to the scheme:

$$K^{\pm} \longrightarrow \pi^{\pm} + \theta^0.$$

The mean lifetime of a K-meson is of the order of 10^{-9} sec.

d) *Tau-mesons* (τ-mesons) have a mass of 970 m_e. Tau-mesons have been encountered with positive and negative charges; they decay into three light mesons:

$$\tau^{\pm} \longrightarrow \pi^{\pm} + \pi^{+} + \pi^{-},$$
$$\tau^{\pm} \longrightarrow \pi^{\pm} + \pi^{0} + \pi^{0}.$$

The mean lifetime of a tau-meson is approximately 10^{-8} sec. Fig. XXXVI is a microphotograph that shows the decay of a tau-meson into three pi-mesons.

e) *Kappa-mesons* ($\varkappa$-mesons). Kappa-mesons have an approximate mass of 1,250 m_e. A probable transformation scheme for kappa-mesons is the following:

$$\varkappa^{\pm} \longrightarrow \mu^{\pm} + 2 \text{ neutral particles.}$$

Hyperons

It has been established that among the tracks of different particles in photographic emulsions there are some to which we must attribute a mass greater than that of a proton. Such particles were called *hyperons.*

Like mesons, hyperons are intermediate particles. But in contrast to mesons, the mass of a hyperon is intermediate between that of a proton (1,836 m_e) and a deuteron (3,672 m_e). Like mesons, hyperons are unstable formations. Their lifetime is of the order of 10^{-10} sec. The decay of a hyperon produces one nuclear particle (a proton or neutron) and a pi-meson.

The neutral hyperon is designated by Λ^0 (the lambda-naught particle). It has a mass of 2,180 m_e and decays into a proton and a negative pi-meson: $\Lambda^0 \longrightarrow p + \pi^-$.

The neutral hyperon has a mean lifetime of 3.7×10^{-10} sec. Fig. XXXVII shows a photograph obtained with a cloud chamber. Clearly visible are the tracks of particles formed

as a result of the decay of a neutral hyperon. The ionizing power and range of these particles are those of the proton and pi-meson. From the range of these particles it is possible to determine the energy of the proton and pi-meson and hence also the mass of the Λ^0 particle from which they were formed. The track of the hyperon itself is not seen; it follows therefrom that the hyperon, whose decay was recorded in the chamber, did not have any charge.

The tracks of charged hyperons have also been observed. The mass of charged hyperons, whose tracks it is possible to detect, proved to be slightly greater than the mass of the neutral hyperon, roughly 2,330 m_e. The mean lifetime of charged hyperons (which are designated as $\Lambda^{\pm}$) has not been determined very accurately. It is something like 3×10^{-10} sec. Probable decay schemes of a charged hyperon are as follows:

$$\Lambda^+ \longrightarrow p+\pi^0$$
$$\Lambda^+ \longrightarrow n+\pi^+$$
$$\Lambda^- \longrightarrow n+\pi^-$$

In these schemes, p denotes a proton, and n, a neutron.

In addition to the tracks of particles of mass 2,330 m_e, there have been found tracks of still heavier particles whose mass was found to be roughly 2,580 m_e (approximately 1.4 proton masses). These particles were called *cascade hyperons*. The accepted designation of a cascade hyperon is the capital letter omega (Ω). So far, cascade hyperons with a negative charge (Ω^-) have been detected. The existence of positively charged and neutral cascade hyperons is not established.

Cascade hyperons are also unstable, decaying within a very short period of time. Their lifetime has not yet been determined. A negatively charged cascade hyperon decays into a neutral Λ^0 hyperon according to the following scheme:

$$\Omega^- \longrightarrow \Lambda^0+\pi^-$$
$$\searrow$$
$$p+\pi^-.$$

A negative cascade hyperon decays into a proton and two negative pi-mesons. However, the proton does not appear at once but as the result of a steplike process. The cas-

cade hyperon is converted into a Λ^0 particle and a π^--meson; this is followed by the Λ^0 particle transforming into a proton and a negative pi-meson. It is precisely because the formation of the stable particle (proton) takes place in two stages, that the primary particle (hyperon) received the name of a cascade hyperon.

Our knowledge of heavy mesons and hyperons is still exceedingly scant. The principal source of information about the properties of these particles is cosmic rays. The intermediate particles are rather infrequently encountered, making the study of their properties a relatively difficult matter. However, much should change in this field in the nearest future.

It has already been mentioned that machines are in operation that are capable of imparting to protons energies over a thousand million electron-volts. Such fast particles can create both heavy mesons and hyperons in laboratory conditions. This will help to speed up work in explaining the unusual properties of the intermediate particles, and to gain an understanding of their nature, and to determine the contribution of these particles to nuclear forces.

A new remarkable discovery was made in December 1955 by means of such an accelerator. The American physicists Chamberlain, Segrè, Wiegand, and Ypsilantis detected particles possessing protonic mass but charged negatively. These particles were termed *antiprotons.*

Scientists had long been in search of such particles. We know of two types of electrons (those with a negative and a positive charge). Pi-, mu-, and K-mesons likewise have both charges. But protons were always encountered only with a positive charge. It might have been expected that if protons could originate like positrons and electrons, there should be a particle of mass equal to that of a proton but with a negative charge. These two particles—proton and antiproton—should originate simultaneously. The creation of such a pair would require an energy of over 4,000 million electron-volts.

Antiprotons were discovered in the bombardment of copper by protons of energy 6,200 million electron-volts. Protons and antiprotons combine and disappear, giving rise to a large number of mesons. However, charged particles,

such as electrons and protons, are not the only ones that exist in the form of antiparticles. Neutral particles have this property, too. Thus, Cork, Lambertson, Piccioni and Wenzel discovered the existence of the *antineutron* (1957). A characteristic feature of antiparticles is that an antiparticle can interact with a particle and become annihilated, giving rise, in the process, to other types of particles. Thus, a positron and electron on uniting disappear, giving rise to two gamma quanta. The joint disappearance of a proton and antiproton results in the birth of a multitude of mesons. The same happens when a neutron and antineutron unite and are annihilated.

The proton and antiproton have identical masses and differ only in the sign of the charge, that of the proton being positive and that of the antiproton, negative. The neutron and antineutron not only have the same mass, they fail to exhibit any difference in charge, which is zero in both cases. Then is there any difference between these particles? Yes, there is. Like the other elementary particles, the neutron possesses a mechanical moment (spin) and a magnetic moment. The antineutron likewise has a mechanical and a magnetic moment. However, if the direction of the mechanical moments of a neutron and antineutron is the same, the magnetic moments will be oppositely directed.

Again About Cosmic Rays

Since the discovery of cosmic rays our conceptions of them have undergone considerable change. It was pointed out earlier that during the early stages of cosmic-ray studies the rays were believed to be an electromagnetic radiation with a very short wave length.

The Bothe-Kolhörster experiments on the one hand and those of D. V. Skobeltsyn on the other established a different hypothesis to the effect that cosmic rays are electrons. However, Skobeltsyn was the first to note that the greater part of the electrons observed are terrestrial in origin. They are created through the interaction of some sort of primary particles with our atmosphere.

At present it is thought that electrons are not the primary cosmic particles. This conviction is based on two facts:

the first is connected with the effect produced by the earth's magnetic field on cosmic particles. We have already noted that the earth's magnetic field deflects incoming cosmic rays to the magnetic poles. Cosmic particles whose energy is not very great are deflected to the poles. However, particles of greater energy are able to reach the equator. The magnetic field acts on cosmic particles because of their charge. What is the charge of cosmic particles? We already know that charges of different sign are deflected in different directions. Calculations show that positively charged particles are deflected by the earth's magnetic field to the east, that is, they move earthward from the west. Negatively charged particles observed near the equator come in from the east.

In order to resolve the problem of the sign of the charge of primary cosmic particles, a group of Soviet scientists headed by S. N. Vernov organized an expedition to equatorial latitudes. There, sounding balloons carried into the stratosphere groups (telescopes) of Geiger-Müller counters which could be oriented westward and eastward by means of a special device. Signals from the telescopes were telemetered to apparatus on the ship. Vernov's investigations showed that the primary cosmic particles moved earthward from the west, and that consequently they carried a positive charge.

It is noteworthy that in 1939 the American Johnson conducted observations to establish the direction of flight of the primary cosmic particles. He arrived at the erroneous conclusion that cosmic particles are equally directed from west to east and from east to west. For nearly ten years this conclusion created confusion in views on the nature of cosmic radiation. Only through the work of Vernov did it become clear that Johnson's conclusion was incorrect; this was apparently because he had not been dealing with primary cosmic particles.

The second fact indicating that the primary cosmic rays are not electrons is this.

It is known that electrons entrant in the earth's atmosphere multiply creating showers. For such a shower to reach the earth's surface without being absorbed in the atmosphere, the primary electron must possess a considerable energy

(of the order of 10^{13} electron-volts). Observations carried out by Vernov showed that there are no electrons of such energies in the upper layers of the atmosphere; which means that it isn't electrons that produce all the numerous secondary particles which we observe at the earth's surface and at low altitudes.

Neither can positrons and mesons be the primary cosmic particles. They are short-lived and are definitely secondary in origin (that is, they originate in the earth's atmosphere).

What are these primary cosmic particles?

Recently much information has been amassed indicating that the predominant part of the incoming cosmic particles is made up of protons.

Of course, we do not observe protons in cosmic radiation at the earth's surface because they are absorbed by the atmosphere. However, at high altitudes there is a rather large number of protons, and their number increases with height.

Protons are not the only particles of cosmic rays. The composition of cosmic radiation is extremely complex.

Certain conclusions concerning the composition of cosmic rays may be drawn on the basis of data obtained in stratosphere flights. Let us again return to Fig. 17. From this figure it may be seen that the intensity of cosmic radiation does not change from an altitude of 50 km. to 160 km. It is not difficult to explain why. In passing through the earth's atmosphere down to these altitudes, the primary particles encounter such a small layer of matter (above 50 km. the layer of matter is equal to one-thousandth of the layer of the entire atmosphere) that secondary processes do not have time to show any perceptible development. For this reason, the bulk of cosmic particles at these altitudes may be regarded as primary particles and, what is more, an appreciable fraction of the primary particles reach lower altitudes.

Observations with photographic plates carried out at altitudes exceeding 25 km. have exhibited high-energy particles with a *large charge*. Such particles have not been found below 20 km. A number of obsevations, and also the fact that even at an altitude of 30 km. these particles have a dominant downward direction, have established that these particles are of primary origin.

How is it possible to distinguish particles with a large charge from other particles? This may be done by checking the magnitude of the ionizing power. Theory states that the ionizing power of a particle varies as the ratio $\frac{Z_2}{v^2}$ where Z is the charge of the particle, and v its speed. Thus, particles with a large charge should possess a tremendous ionizing power (see Appendix, Fig. IX). The tracks of these exceedingly heavily ionizing particles were observed in emulsions of photographic plates raised to heights of 30 km. An idea of the ionizing power of such particles may be gained from Figs. IX and XXXVIII (see Appendix).

Fig. IX shows a track formed by a particle in a photographic emulsion. The ionization produced by this particle is so great that its track does not exhibit the individual grains but forms a continuous strip of developed silver. The accompanying scale gives an idea of the size of this strip. Fig. XXXVIII shows in comparison the pictures of a track left in the emulsion by an alpha particle emitted in the decay of thorium and the tracks left by a cosmic particle with a big charge. It may be seen that the ionization produced by such particles increases with the decreasing energy of the particles. Judging from its ionizing power and range, the charge of this particle is equal to 15 elementary units.

A study of such multiple-charged particles showed that there are some among them with charges from *six to forty*. What are these particles with such a big charge?

A careful examination of tracks left by them in the emulsion of a photographic plate is convincing evidence that they are the nuclei of heavy elements. When the energy of these nuclei decreases greatly they begin to capture electrons, which is seen from their diminishing ionizing power. The process of electron capture continues until the electron shells of these atoms are completely filled.

A remarkable fact was the distribution of heavy particles according to size of charge (see Fig. 45). It is in accord with astronomical data on the distribution of elements in the universe. For example, the elements lithium, beryllium and boron (the insignificant occurrence of which is well

known to astrophysicists) have not been found among the primary cosmic particles.

Another remarkable property discovered in these experiments was the relationship between the charge of the particle and its energy. The energy of the particles turned out

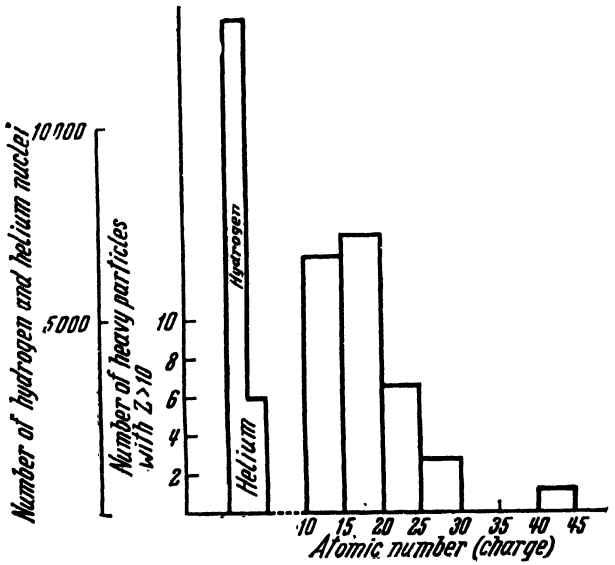


Fig. 45. Distribution of multiple-charged particles of cosmic radiation according to magnitude of charge. The distributions are given for hydrogen and helium and for particles whose Z exceeds 10. On the ordinate axis are two scales: one for hydrogen and helium, and the other for particles with $Z > 10$.

to be proportional to the charge. For each unit of charge there is an energy of two to three thousand million electron-volts.

The total number of heavy cosmic particles (with a nuclear charge exceeding 10) is such that one particle enters each square centimetre per hour (in a solid angle of unity). This means that heavy particles comprise $\frac{1}{400}$ of the number of protons moving earthward.

To summarize, the primary cosmic radiation is complex in composition; it consists principally of protons and helium nuclei (the latter are only four times less in number than protons); besides them there are nuclei of heavy elements right up to niobium.

What happens when a primary cosmic particle (a proton or a nucleus with a large charge) enters the earth's atmosphere?

For a long time there was no answer to this question. Now, thanks to the numerous and extensive investigations of D. V. Skobeltsyn and co-workers, chiefly N. A. Dobrotin and G. V. Zatsepin, the general outline of the phenomena that attend the entry of primary particles into the earth's atmosphere is now clear-cut. D. V. Skobeltsyn believes that resulting from the interaction of a primary cosmic particle with atomic nuclei there occur "nuclear explosions" accompanied by the formation of beams consisting of a large number of particles. Photograph XXXIV shows the tracks of particles produced in such an explosion. The explosion was caused by a particle with a charge of 13, that is, a nucleus of aluminium. Among the particles produced in a nuclear explosion, there are frequently many which themselves are capable of exploding new atomic nuclei. The result of such explosions is a shower of particles. But these showers are essentially different from showers created by electrons or high-energy gamma quanta. The difference between these showers lies both in the mechanism of shower origin and in the nature of the particles that comprise the shower.

Electronic showers are produced in the area adjacent to nuclei and consist of electrons, positrons and gamma quanta. Showers resulting from nuclear explosions originate in processes that occur inside nuclei and consist of three types of particles. The first group comprises nuclear particles—protons, neutrons, the heavier nuclear fragments, hyperons and heavy mesons. This group contains the particles that develop showers by creating new nuclear explosions. The second group are particles that do not produce showers and are apparently nuclear-inactive mesons. And, finally, the third group of particles consists of electrons and positrons, which do not originate directly in the nuclear explosion but are the decay products of mesons.

All these complex transformations may be represented diagrammatically as follows:

$$\text{Primary protons} \longrightarrow \left[\begin{array}{l}\text{electrons,}\\ \text{mesons,}\\ \text{nuclear-active particles}\end{array}\right] \rightarrow \left[\begin{array}{l}\text{cascade}\\ \text{processes}\\ \text{(showers)}\end{array}\right]$$

The presence among the products of "nuclear explosions" of both nuclear particles and of electrons was the reason why the beams of particles produced in explosions are called electron-nuclear showers. Fig. XXXIX shows a photograph of such a shower obtained in a cloud chamber.

Chapter IX

THE NEUTRINO

Beta-Ray Spectra

In this chapter we shall deal with one of the most complicated and involved problems of nuclear physics, that of the nature of beta spectra.

Even during the early stages of the study of radioactive substances, scientists attempted to measure the energy of the particles emitted in the process of radioactive decay. By the method, already familiar to the reader, of deflecting particles in magnetic and electric fields, and as a result of painstaking efforts, scientists succeeded in measuring both the mass of the emitted particle and its energy. Such investigations were carried out for all radioactive emitters. It was in this work that a fundamental difference was discovered between substances emitting alpha and beta rays.

It was found that each substance that emits alpha particles in radioactive decay does it in such manner that the particles are of a definite energy peculiar only to the given substance. Alpha particles emitted by different radioactive substances have different energies. At present, the energies of the alpha particles of all radioactive alpha emitters have been measured, and we are able to establish the nature of the radioactive substance from the energy of the particles. And by applying the known laws of alpha decay we are even in a position to predict the energy of alpha particles for unknown radioactive substances that have not yet been discovered in nature.

Quite different is the behaviour of radioactive substances that radiate beta particles. When measurements were made of the energy of electrons emerging in the process of radioactive beta decay it was noticed at once that each radioac-

tive isotope does not emit electrons of a single definite energy (as is the case with alpha radioactive substances), but emits a whole set, a spectrum of electrons of totally different energies beginning with zero and ending with a certain limiting value. This limiting value of energy, called the limit of the beta spectrum, is a characteristic value for each beta emitter. By way of illustration, Fig. 46 shows the beta spectrum that originates in the decay of radium E.

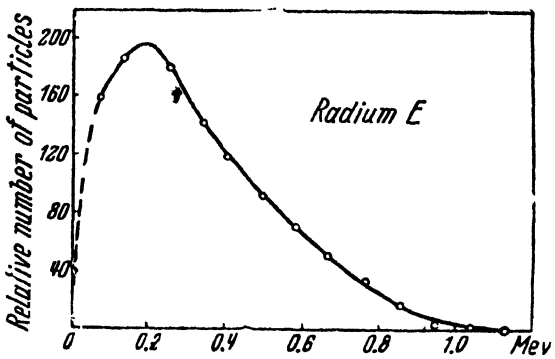


Fig 46. Beta spectrum of electrons emitted by radium E. The energy in millions of electron-volts is plotted on the horizontal coordinate, while the vertical coordinate indicates the relative number of electrons.

This curious result called for an investigation into the nature of the strange character of beta spectra. The uniform energy of alpha particles emitted in alpha decay was no cause for surprise. It seemed natural, and what is more, obligatory. Indeed, do we not find a certain surplus energy in the nuclei of any radioactive substance, which is released in radioactive decay? But all the atomic nuclei of a given radioactive isotope are identical. And so the excess energy of all nuclei of a given isotope should also be the same. It is quite natural that the alpha particles that carry off the surplus energy should have the same energy. I repeat that this circumstance did not seem surprising and was taken for granted. The startling thing was the behaviour of

the beta emitters. Why do the particles of beta decay have different energies? Why is the energy spectrum of these particles expressed by a continuous line from zero energy to a certain limiting value?

We know that each individual electron which we observe originates in the transformation of a nucleus of the given substance. But all nuclei of one and the same isotope are identical. Usually, prior to each beta decay there occurs one or several alpha decays in the process of which alpha particles of the same energy emerge. This may serve as an illustration of the identity of all the nuclei of a given radioactive isotope.Quite often a beta transformation is followed by an alpha transformation. The alpha particles of these subsequent transformations likewise have a very definite energy. This confirms the fact that the energy of different nuclei is the same prior to and following a beta transformation.

What then is the cause of the continuous spectrum of beta rays? For if all nuclei of the initial radioactive substance have the same energy and all the nuclei of the product substance also have one and the same energy, it would seem that the energy of the electrons emitted in the process of beta decay should be identical for all electrons, as is the case with alpha particles. But this doesn't turn out to be so: beta rays do not have the same energy, but a continuous spectrum of energies; true, the upper limit is very definite.

This upper limit in the continuous spectrum was what enabled the following suppositions concerning the causes of its origin to be expressed.

It is possible that all electrons emerging from the nucleus have, at the instant of emergence, the same energy equal to the energy of the limit of the spectrum, but it may be that subsequently not all the electrons retain their energy. For example, it is known that fast electrons can lose their energy by producing radiation. Is it not possible that they lose their energy in different ways from the source to the point of observation?

Some workers advanced the hypothesis that the excess energy in nuclei is not always conveyed to the electrons. Maybe a part of the energy is released from the nucleus in the form of gamma rays? Maybe in some nuclei the greater

part of the energy is transferred to electrons while in others to gamma rays? This could also be a cause for differences in electron energies. It seemed that the verisimilitude of this assumption found confirmation in the well-known fact that beta radiation is frequently accompanied by gamma radiation, whereas in alpha decay gamma rays are exceedingly rare.

Ellis and Wooster undertook to investigate this phenomenon. First of all they decided to check the principal fact: do the electrons take up all the energy released in beta decay, or is a part of this energy released in the form of some other kind of radiation. Their reasoning was this: we know how many electrons are emitted in unit time by a given radioactive substance; we are able to measure the number of electrons that possess a given value of energy, that is, to determine the spectrum of the beta particles. If we know the number of electrons and their energies, we can calculate the sum total of these energies, that is, we can determine the energy of all the electrons emitted by the substance under investigation in one second.

Since the number of electrons of energy equal or close to the limit of the spectrum is very small, the total electron energy will be appreciably less than the product of the number of electrons and the limiting value of their energy. In reality, the total energy of the electrons will equal the product of their number and a certain mean value of energy.

Following the reasoning of Ellis and Wooster, we may say that if we know the beta-particle spectrum we will know the energy carried off by the electrons in decay. The question now is how to determine the energy released in decay?

Let us surround the radioactive emitter with a lead filter of thickness such that all the X-radiation and gamma rays are absorbed in this shield. Naturally, all the electrons will also be absorbed in this filter; hence, the filter will absorb all the energy released by the radioactive substance in beta decay. The problem of measuring this energy is handled as follows: the energy absorbed in the lead causes it to heat up, raising its temperature. From the temperature rise it is possible to calculate the energy absorbed in the lead, that is, the total energy released in the process of decay.

And so, by measuring the electron spectrum (and the number of electrons emitted by the radioactive substance), we determine the energy carried off by the electrons; by measuring the temperature of the lead filter, we determine the total energy released in the decay. A comparison of these two figures will give us the answer to the question of whether all the decay energy is released in the form of electron energy or a part of it is disposed of in some other way.

However, to resolve this problem was not so easy as it seemed. The energy released by decay is relatively insignificant and the thick lead filter does not heat up appreciably. To avoid possible errors, Ellis and Wooster prepared two absolutely identical calorimeters, into one of which they placed the radioactive emitter, while the other remained empty. By comparing the temperature of both calorimeters they were able to determine rather accurately the energy released by the radioactive substance. In their experiments radium E was used as the radioactive emitter. The beta spectrum of radium E (see Fig. 46) was thoroughly studied by Ellis and Wooster themselves. They found the limit of the beta spectrum of radium E to be 1.05 million electron-volts. A measurement was also made of the mean energy of the electrons emitted by radium E. It turned out 0.39 million electron-volts. And finally, the thermal measurements with the calorimeter were completed. The results did not only fail to explain the secrets of the beta spectrum, but on the contrary confused the problem still more. The measurements with a lead calorimeter showed that radium E emits an average energy of 0.35 million electron-volts per disintegration. Taking into consideration the inevitable errors in such delicate measurements, one had to regard this number as being in good agreement with the mean electron energy (0.39).

To summarize, *the energy carried off by electrons represents the total energy released in beta decay*. Then what is the cause of continuity in beta spectra? This proved to be a problem of extraordinary difficulty.

The difficulties involved in resolving this problem were so great that some scientists even began to question the very law of the conservation of energy. Thus, Bohr put forth a hypothesis stating that the law of conservation of energy breaks down in beta decay.

In Bohr's opinion, all nuclei of a beta emitter are undoubtedly identical, just as are the nuclei of the product substance of the decay. The excess energy produced as a result of radioactive transformation is always the same. In the case of the conversion of radium E to radium F this excess is 1.05 million electron-volts. However, Bohr says, the electron does not always receive this energy. Sometimes it receives this energy in full, but sometimes only in part. And what of the remaining part of the energy? It disappears without a trace. According to Bohr the law of the conservation of energy is not observed in beta decay.

But Bohr's arguments contradicted the fundamentals of physics, for the law of the conservation of energy is the foundation on which rests every physical theory. Suffice it to recall the law of radiation of light quanta formulated by Bohr himself. It is nothing other than the law of conservation of energy as applied to the electronic shells of the atom and to radiation. The atom radiates a quantum of electromagnetic energy of magnitude equal to the reduction of internal energy of the atom which, in the act, passes to a lower energy level. In the final analysis, the greater part of our preceding conclusions concerning the nucleus and the elementary particles rest on the law of the conservation of energy.

The Pauli Hypothesis

The Swiss physicist Pauli was the one who showed a way out of this difficulty.

He believed that the law of the conservation of energy should hold in the beta decay process just as it does in all other phenomena. If such is the case, then all the disintegrating nuclei should release one and the same energy. But electrons have extremely diverse energies, which means that the energy released in decay is taken up not only by electrons. Obviously, there must be some other particle which carries off a part of the beta-decay energy. Thus Pauli says that in the beta-decay process the nucleus ejects not one particle (electron), but two: an electron and some other particle which had not yet been discovered. All the energy is distributed between them. In some cases both particles re-

ceive equal energy, in others the electron receives the greater part, and in still others the smaller part. In some cases, the electron takes up all the energy. This corresponds to the limit of the spectrum. And of course there are cases where this unknown particle takes up all or nearly all the energy of beta decay. The number of such cases is rather large and for this reason the mean electron energy is not equal to one half of the limit energy of the spectrum, but is slightly less.

Pauli's hypothesis did away with the contradiction to the law of the conservation of energy. But it was still necessary to bring this hypothesis into agreement with the results of the Ellis-Wooster experiments, for these experiments, begun with the express purpose of verifying the view that electrons take up only a part of the decay energy, seemed to be unambiguously in opposition to this view. According to the data of Ellis and Wooster, the thick lead filters absorb as much energy as the electrons had and no more. Pauli was not deterred, he considered that the new particle in question was not absorbed by the lead at all or so insignificantly that this absorption was not detected in the experiments of Ellis and Wooster.

What was this particle and what properties could it be expected to have?

Straight off it might be stated that this particle has no charge, otherwise it would easily be detected in deflection experiments in electric or magnetic fields, and, besides, a charged particle of energy of the order of one million electron-volts could not pass through a thick lead filter. Therefore, the Pauli particles cannot be charged, they are neutral. We are already acquainted with one neutral particle, the neutron. However, it is easy to see that the neutron cannot be the particle whose existence Pauli had theorized. Firstly, neutrons are absorbed, though not very strongly, by a lead filter. Secondly, the ejection of neutrons (in addition to electrons) from the nucleus in beta decay could easily be detected by the change in mass of the nuclei (when a neutron leaves a nucleus it carries with it a unit of mass). And finally, the neutron (if that is what it is) would exhibit itself in collisions with other atomic nuclei. However, such collisions were not observed. Obviously, the neutron could

not be the Pauli particle. The only thing left was to suppose that the particle released in beta decay together with the electron was an utterly new particle that had not hitherto been observed in any physical phenomena.

Pauli assumed this particle to have a mass equal to that of an electron, and called it a "*neutrino*" (the Italian diminutive for neutron). This was how the neutrino came into existence.

But the birth of the new particle was not accompanied by a "triumphant sounding of bells." The existence of the neutrino was not confirmed by such incontestable facts as was the existence of neutrons, positrons, mesons and hyperons. Actually, there were no physical data confirming the reality of the existence of the neutrino, excepting the fact of continuity of the beta spectrum. And what is more, it was necessary to attribute to the neutrino such properties as made it seem highly improbable that this particle could be detected in any physical experiment.

All the facts concerning the neutrino are negative. We know it has no charge, that it does not possess any magnetic properties, that it does not interact with nuclei and electrons and does not collide with them, or if it does, it does not transfer to them any perceptible energy. Experiments were conducted that showed that if the neutrino does exist it ionizes so weakly that in 500,000 km. of air it could create no more than one ion pair; it is therefore not surprising that many physicists regarded the particle proposed by Pauli very sceptically. Indeed, it was no easy matter to believe in the existence of the neutrino.

However, the neutrino hypothesis still pointed to a possible way out of the impasse resulting from the established continuity of the beta spectrum. It was for this reason that attempts continued to prove the actual existence of the neutrino.

In 1934, Fermi worked out a theory involving the neutrino based on Pauli's views. This theory explained many details and peculiarities of beta spectra. In 1935, the Soviet scientist A. I. Leipunsky devised an experiment that might show the existence of the neutrino. Here is how Leipunsky argued.

New particles are ejected from the nucleus in beta decay.

Therefore, we should observe a phenomenon similar to the recoil of a gun. Just as a gun recoils after its shot, there should be a *nuclear recoil* in beta decay (incidentally, this should also occur in other types of decay). The nucleus that has ejected a particle should recoil in a direction opposite to the direction of the ejected particle. Obviously, the recoil experienced by a nucleus in beta decay will differ depending on whether one particle (electron) or two particles (electron and neutrino) are ejected from the nucleus.

According to the Pauli hypothesis, the excess energy of the nucleus is transferred in beta decay to an electron and a neutrino. In the case of the decay of radium E, an electron receives an average of only 0.39 million electron-volts, while the remainder (0.66 million electron-volts) is taken up by a neutrino. A nucleus that simultaneously ejects a neutrino of energy 0.66 million electron-volts and an electron of energy 0.39 million electron-volts should obviously experience a considerably greater "recoil" than in the case of the ejection of one electron of energy 0.39 million electron-volts. Leipunsky's idea was to attempt to find data confirming the origin of neutrinos in the process of beta decay by studying nuclear recoils, inasmuch as it was impossible to detect a neutrino by its interaction with matter. However, to put this idea in practice in 1935 was an extremely difficult matter, and Leipunsky himself did not succeed in obtaining completely unambiguous results. Much later, in 1942, Allen repeated the Leipunsky experiment in a slightly modified form. But before describing Allen's experiments I shall relate about one more interesting phenomenon.

K-Capture

In 1935, Møller noticed that radioactive substances, which in the process of decay emit positrons, could also undergo another transformation. Indeed, a nucleus of ${}_{23}V^{48*}$ emitting positrons and experiencing a transformation according to the scheme:

$$ {}_{23}V^{48*} \longrightarrow {}_{22}Ti^{48} + {}_{+1}e^{0} \text{ (positron)}, $$

converts into ${}_{22}Ti^{48}$. However, the isotope ${}_{23}V^{48*}$ could turn into ${}_{22}Ti^{48}$ by a process other than positron ejection. It would be enough for ${}_{23}V^{48*}$ nucleus to capture one of the orbital electrons of the atom. In this case, the mass of the nucleus will remain without change, while the charge is reduced by unity just as occurs in positron decay.

The scheme of such a transformation should be written as follows:

$$ {}_{23}V^{48*} + {}_{-1}e^{0} \text{ (electron)} \longrightarrow {}_{22}Ti^{48}. $$

The capture of an orbital electron by an atomic nucleus should proceed in accord with the same laws as radioactive decay. Such a process may be quantitatively characterized by a certain "capture constant" analogous to λ, the constant of radioactive decay. We may introduce the concept of "period of half-capture" (the counterpart of the "half-lifetime") which denotes the time required for one half of the atoms to accomplish capture of one of the orbital electrons by the nucleus.

Thus, two radioactive processes may occur with radioactive nuclei of ${}_{23}V^{48}$ type that undergo positron beta decay. The question as to which of them is predominant is determined by the relationship of the constants of capture and decay. If the decay constant is very much greater than the capture constant, decay will occur more often than capture; if, on the other hand, the constant of radioactive decay is less than the capture constant, transformation of nuclei caused by electron capture will occur more often.

How is it possible to detect the capture process of an orbital electron by an atomic nucleus? The ordinary procedures used in the study of radioactivity cannot be applied here. In radioactive transformations a certain particle is ejected from the nucleus. By registering this particle we know that radioactive decay has occurred. But in orbital-electron capture by a nucleus there is no ejection of particles from the nucleus, and so we cannot locate radioactive capture by the appearance of any new particles.

The method of detecting electron capture was proposed by Alvarez. To understand Alvarez's idea, recall that the electrons in atoms are distributed in orbits. The two electrons that comprise the so-called *K*-shell are closest to

the nucleus. It is therefore natural to expect that the nucleus will capture electrons chiefly from this group.

Let us assume that precisely such a capture has taken place. What will follow?

A nucleus of vanadium that captures one electron will convert into a nucleus of titanium. The charge of the titanium nucleus will be one unit less than that of the nucleus of vanadium. An atom of titanium normally contains twenty-two extra-nuclear electrons because the nuclear charge of titanium is 22. The electron configuration of an atom of vanadium contains twenty-three electrons; one of them is captured by the nucleus, leaving 22, that is, as many, it would seem, as necessary. However, if during transformation a nucleus of vanadium captures an electron from the *K*-group (this case is termed *K*-capture) the electrons in the newly formed atom of titanium will not be disposed correctly. In group *K* there will be only one electron, whereas there should be two. On the other hand, there will be one extra electron among the outer valence electrons since vanadium has five valence electrons, whereas titanium should have only four. Summarizing then, a titanium atom produced in the transformation of vanadium will have one extra valence electron and one electron lacking in the *K*-group. The extra valence electron will finally pass over to the *K*-group. It will be recalled that in this process, *X*-rays characteristic of titanium will be emitted. The appearance of titanium X-rays emerging from vanadium will indicate that a *K*-electron has been captured by the nucleus.

Alvarez made a thorough study of the radiation emitted by ${}_{23}V^{48}$ and discovered, in the latter, the characteristic X-rays of titanium. This was proof of the existence of *K*-capture. By comparing the quantity of positrons and quanta of the characteristic radiation of titanium, it is possible to determine which of these phenomena (positron decay or *K*-capture) occurs more frequently. It was found that in the case of "vanadium-48" both processes are roughly of the same probability.

As soon as the results of Alvarez's work became known, scientists immediately began checking other nuclear transformations that proceed with positron emission.

In many cases *K*-capture was detected. The nuclei of

calcium-41, scandium-46, chromium-51, manganese-52 and 54, cobalt-56 and 57, copper-61 and 64 and many others convert by means of *K*-capture. At the present time, there have been recorded some 40 different transformations that occur by *K*-capture. Among these different transformations there are such (as in vanadium-48) that the transformation by *K*-capture is nearly as equally probable as the transformation attended by positron emission. However, in some substances positron emission is predominant. In others, on the contrary, *K*-capture comes first.

The transformation of a beryllium-7 nucleus turned out to be of special interest.

Beryllium-7 is a radioactive isotope of one of the lightest elements. The light elements have very few isotopes and for this reason it is possible to predict straightaway what the nuclear transformation should be.

Only lithium has a stable isotope of mass seven. Lithium has an atomic number one unit less than beryllium. For this reason it was to be expected that the transformation of a radioactive nucleus of beryllium-7 into a stable nucleus of lithium-7 would occur by means of *K*-capture or through positron emission. However, the attempts made showed that beryllium-7 does not emit positrons at all. This suggested that all beryllium-7 nuclei are transformed by means of *K*-capture. But how is one to detect *K*-capture in beryllium?

Since the element lithium produced in the *K*-capture of beryllium has a nucleus with a small charge of only three units, the X-rays produced in this capture consist of such low-energy quanta that it is impossible to detect them. But an accident helped. It was found that beryllium-7 is radioactive and is transformed into a stable isotope of lithium by means of *K*-capture as was thought.

Earlier it was noticed that when, as a result of nuclear transformations, there is formed a stable isotope of lithium (Li^7), a part of the nuclei produced (roughly 10 per cent of the total number) will be in an excited state with an excess energy of 0.45 million electron-volts. As usual in such cases, this excess energy is radiated by the nucleus in the form of a gamma ray. Through a happy coincidence, the origin of lithium-7 nuclei is accompanied by a peculiar signal—the emission of gamma quanta of energy 0.45 mil-

lion electron-volts. This was what helped to establish the fact that beryllium is radioactive.

Beryllium-7 is formed for example in the bombardment of lithium-6 by deuterons:

$$_3Li^6 + _1D^2 \longrightarrow _4Be^7 + _0n^1.$$

It was found that the emission of gamma rays of energy 0.45 million electron-volts also occurs after bombardment of lithium-6 by deuterons. The intensity of gamma radiation diminishes with time just as in the case of other radioactive substances. In 43 days the intensity of gamma radiation decreases by one half.

Chemically, it was established that this radiation is connected precisely with the beryllium that is formed through the bombardment of lithium by deuterons. Consequently, beryllium-7 is radioactive and converts into lithium-7, a part of the nuclei of which originate in an excited state, thus accounting for the appearance of gamma rays of energy 0.45 million electron-volts. Beryllium-7 has a half-life of 43 days. Since the transformation of beryllium-7 into lithium-7 is not accompanied by positron emission, it can be accomplished only through the agency of *K*-capture.

Thus, beryllium-7 proved radioactive and is transformed into lithium-7 *by means of K-capture only*. This circumstance played an important part in deciding whether the neutrino really does exist or not. But what has beryllium-7 got to do with the neutrino? Was it not through the necessity of understanding the continuous nature of the beta spectrum that the existence of the neutrino was hypothesized? This was precisely what made Pauli suggest that a neutrino accompanies the electron that appears in beta decay. A study of the spectrum of positrons which appear in positron decay showed that this spectrum is of the same nature as the electron spectrum in beta decay. Consequently, positron radiation should also be accompanied by a neutrino.

But positrons do not appear in the transformation of beryllium-7. Still, in this case also, one may expect the appearance of a neutrino for the very same reasons that a neutrino arises in beta decay. This is first of all a result of the action of the energy conservation law, because the energy

of a beryllium-7 nucleus differs from that of a normal nucleus of lithium-7. The transformation

$$_4Be^{7*} + _{-1}e^0 \longrightarrow {}_3Li^7$$

should release an energy of 0.8 million electron-volts. How is this energy released? Since no particles are ejected from the nucleus they cannot carry off the excess energy. Gamma rays likewise do not arise. The above-mentioned gamma rays of energy 0.45 million electron-volts originate in a lithium nucleus after the transformation of beryllium has taken place, while in itself the process of the transformation of beryllium-7 into lithium-7 is not accompanied by the emission of gamma rays.

Thus, neither gamma quanta nor positrons originate in the transformation of beryllium-7 into lithium-7. Then how is the excess energy removed from the lithium-7 nucleus that is produced in this transformation? We are forced to assume that there exists some kind of neutral particle which we do not detect but which carries off this excess in the form of its kinetic energy, that is, again we arrive at the neutrino hypothesis. But here the situation is slightly different, since only one particle (neutrino) is ejected from a beryllium nucleus. Therefore, if a beryllium nucleus recoils, this recoil is due precisely to the neutrino and not to anything else. If it were possible to detect this recoil, it would be one more argument in favour of the neutrino hypothesis.

We must say that the transformation of beryllium-7 into lithium-7 is the most convenient case for detecting the existence of recoil of nuclei. Beryllium-7 is one of the lightest isotopes. This is very important because the lighter the nucleus the greater will be the recoil. Also, since nothing is ejected from the nucleus other than a neutrino, all nuclei should experience the same recoil. These peculiarities play an essential role in the successful execution of nuclear recoil experiments.

The Soviet scientist A. I. Alikhanov was the first to grasp the remarkable properties of beryllium-7. In 1939, he began very interesting experiments to observe the recoil of nuclei. Because of the war, Alikhanov was not able to complete these investigations.

Allen's Experiments

In 1942, Allen carried out the following experiments (Fig. 47).

A thin film of beryllium-7 was deposited on a plate *A*. It was very important to obtain beryllium in the form of a monoatomic layer on this surface. Allen solved this difficult problem. The energy of the recoil nuclei obtained in the emission of a neutrino by beryllium is only 80 electron-volts. A nucleus that recoils in such manner is ejected in the form of an ion. In order that the ion should arrive safely at the point of observation, it was necessary to degas the plate itself on which the beryllium-7 was deposited, and also create the best possible vacuum in the apparatus, in which these ions were to move. And in order to have favourable conditions for removing the recoil ions from the surface of the plate, Allen placed in front of it a grid *B*, thus creating between the grid and plate *A* an electric field to accelerate the positive ions. The action of this grid on the ions is analogous to the action of the control grid in an amplifying radio valve. It enables us to extract electrons from the cathode of the valve In Allen's experiments, grid *B* also helped to draw out ions of lithium-7 that originated on plate *A* from recoil.

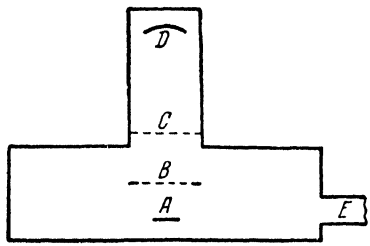


Fig. 47. Schematic diagram of Allen's experiment.

A — plate with radioactive source ^{7}Be; *B* and *C* — grids; *D* — collecting electrode of ion counter; *E* — tube to vacuum pump.

When the recoil nuclei traversed the electric field between plate *A* and grid *B*, their energy increased at the expense of the electric field. In Allen's experiments this energy increase came to roughly 100 electron-volts. After grid *B* the ions entered another electric field between grids *B* and *C*. Here the electric field was directed so that the ions that had passed grid *B* were decelerated by the field. By varying the magnitude of field *BC*, it was possible to

achieve a situation in which none of the ions passing grid B would be able to reach grid C. To do this, field BC had to be such that an ion in it lost not only the energy acquired in electric field AB, but also the energy obtained in recoil.

If, however, the BC field is less than the above-mentioned value, the recoil nuclei will pass through grid C, and enter an accelerating electric field of several thousand volts, after which they are caught by a special counter placed at D.

Thus, the registration of ions by counter D will show whether any charged particles have passed through field BC or not. The experiment showed that recoil nuclei do exist and that their energy is 80 electron-volts, that is, it fully coincides with the value that might be expected if the recoil is really due to a neutrino.

In order to eliminate entirely any possible doubts as to whether the recoil was caused not by a neutrino, but say by gamma rays, Allen carried out control experiments. His argument was this: if recoil is due to the ejection of a gamma quantum, the recoil nuclei must appear simultaneously with the gamma quanta. But a gamma quantum is not a neutrino. The former can be registered by a counter independently of the recoil nucleus. Therefore, if we put two counters, one of which is designed to count gamma rays and the other, recoil nuclei, we should observe coincident discharges in the two counters. However, nothing of the sort was observed. This was grounds for concluding that the appearance of recoil nuclei is not caused by gamma rays.

Thus, to summarize, in the process of the transformation of beryllium-7 into lithium-7 which proceeds by means of K-capture, lithium-7 nuclei experience recoil. The momentum that corresponds to this recoil is obviously carried off by some kind of particle. This circumstance makes the hypothesis of the neutrino (a particle without an electric charge, without a magnetic moment, and of mass no larger than that of an electron) highly probable.

A thorough study of the beta spectrum of ${}_1H^3$ (triton) showed that the mass of the neutrino is indeed considerably less than the mass of an electron. It has not been possible to make an exact determination of the mass of the neutrino, but it may be stated definitely that it does not exceed 1/1,000 of that of an electron.

Chapter X

THE STRUCTURE OF ATOMIC NUCLEI AND THE FORCES ACTING BETWEEN NUCLEAR PARTICLES

We have already learned about many phenomena that involve atomic nuclei. It is now time to pose the question of the structure of atomic nuclei, to find out what particles comprise them, and what forces act between these particles.

It has already been pointed out that earlier, when phenomena related to natural radioactivity was all that was known, it was believed that atomic nuclei consisted of alpha particles, protons and electrons. Since that time we have learned of the existence of other elementary particles, neutrons, positrons, mesons and the neutrino. All these particles play different parts in phenomena that involve atomic nuclei. In nuclear transformations we observed neutrons, positrons and neutrinos as well as protons and alpha particles. The interaction of fast protons and neutrons with atomic nuclei produces pi-mesons. Do all these particles go to make up the nucleus of an atom? The answer is no.

Are There Electrons in Atomic Nuclei?

Let us first examine the hypothesis which states that nuclei consist of protons and electrons. This hypothesis led to a number of contradictions with experiment. Among them are the following:

1. *Magnetic properties of atomic nuclei.* Let us take a simple nucleus, such as a deuteron. Its mass is two and its charge unity. According to the hypothesis at hand, the deuteron should consist of two protons and one electron. Both

the proton and electron possess magnetic properties. The accepted way of describing the magnetic properties of particles is by their magnetic moments.

The magnetic moments of a proton and electron are not identical: the moment of a proton is nearly one thousand times less than that of an electron. If the hypothesis saying that a deuteron consists of two protons and one electron is correct, then what kind of magnetic moment should one expect the deuteron to have? The answer, of course, is simple. Since the magnetic moments of protons are small in comparison with the electronic magnetic moment, one should expect the magnetic moment of a deuteron to be close to that of an electron. Experiment, however, shows that this is not so in the least. The magnetic moment of a deuteron proved less than the magnetic moment of a proton!

The natural question is: If the nucleus of a deuteron really does contain an electron, then why does its magnetic field disappear?

We selected the nucleus of heavy hydrogen as an example. But this contradiction applies to all nuclei. The magnetic moments of all nuclei are small in comparison with the magnetic moment of an electron.

2. *Nuclear spin.* The term spin in reference to the motion of a top is familiar to everyone from childhood. A top is a body capable of rotating rapidly about its axis. Rotary motion is described by a magnitude called angular momentum. Every rotating body possesses a definite angular momentum. It turns out that all the elementary particles: the electron, proton, positron, neutron and neutrino also have angular momenta. It would not be correct to think that these small particles are really "miniature tops," that is, tiny solid bodies rotating about their axes. First of all, the very fact that they are capable of transformations, that is, of appearing and disappearing, and becoming other particles in the process, proves that they are far more complex objects. However, they do possess an angular momentum, the nature of which has not been fully established. But unlike a top, whose angular momentum constantly diminishes due to friction of the surface on which it moves, the angular momentum of a proton and an electron always remains constant.

The angular momentum is just as distinguishing a feature of elementary particles as is their charge. For this reason, the angular momentum was given a special name, "spin." The magnitude of the spin is expressed by a special unit, which is equal to Planck's constant h divided by 2π. In these units, the spin of a proton and the spin of an electron are expressed by the number $\frac{1}{2}$.

If any two particles, each of which has a spin of one half, unite, the newly formed complex system will have a spin of either zero or unity. The spins combine giving a resultant value of unity if the directions of the angular momenta of both particles are the same. If the angular momenta are in opposite directions the value of the spin of the whole system will be equal to the difference of the spins of both particles, that is, zero. These rules for adding spins permit of predicting with ease the value of the spin of a nucleus if we know the number of particles that comprise it. If the number of particles is even, the spin will be either zero or integer. If the number of particles is odd, the resulting spin will be either $\frac{1}{2}$ or $\frac{3}{2}$, or another odd number of halves.

The difference between the two cases is very great. The behaviour of particles that have an integral spin differs sharply from that of particles with a spin of an odd number of halves. In practice therefore it is easy to differentiate these two cases.

Let us apply this rule to atomic nuclei. We again take deuteron as an example. On this hypothesis a deuteron consists of three particles, and therefore its spin must be either $\frac{1}{2}$ or $\frac{3}{2}$. But experiment established the spin of a deuteron at unity. The nitrogen nucleus was found to have the same contradiction. The mass of a nitrogen nucleus is equal to fourteen mass units. Therefore, it has 14 protons. Nitrogen has an atomic number of 7. Consequently, there should be seven more electrons in the nitrogen nucleus, or a total of $14+7=21$ particles.

If the number of particles is odd, the spin will be equal to an odd number of halves. However, precise spectral investigations have shown that the spin of nitrogen is in-

tegral. This circumstance seemed so contradictory that it became known in the history of science as the "nitrogen catastrophe."

3. *The energy of electrons in the nucleus.* One more contradiction may be added to those connected with the concept of electrons inside atomic nuclei.

The development of atomic physics led to the creation of a special theory, "wave mechanics," which describes very accurately such phenomena of the "microcosmos" as molecules, atoms and atomic nuclei.

If the rules of this theory are applied and a calculation is made of the energy that an electron should have if it were inside the nucleus (the size of which is of the order of 10^{-13} cm.) the number found is immeasurably greater than the experimental value.

According to the "wave mechanics," electrons (and also other light particles, positrons and neutrinos) cannot exist inside atomic nuclei. Consequently, nuclei do not have electrons. This also means that the difficulties with magnetic moments and spins arose as a result of a misconception concerning nuclear structure.

If there are no electrons in nuclei, it is obvious that the nuclear magnetic moments should not be so big as would be expected if electrons were present there. It is also obvious that the contradiction with the size of the spin was the result of an incorrect count of the number of nuclear particles.

What Are Atomic Nuclei Made of?

Nuclei do not consist of protons and electrons, that is obvious. But they are without question complex structures, for the spin of many nuclei is integral, and, as we have already pointed out, the integrality of the spin is a true sign of complex structure.

Then what are these particles that comprise nuclei? The answer is this: *atomic nuclei consist of protons and neutrons; they have no electrons, positrons or neutrinos in them.* Take a deuteron nucleus, it consists of one neutron and one proton. Such a formation has a mass of two, and a charge of unity, which corresponds to a deuteron, $_1D^2$.

On the new hypothesis, a deuteron contains only two particles (an even number), and not three, as had been supposed earlier, which is in good agreement with the magnitude of the spin of the deuteron, equal to unity, as you remember.

According to the new picture, a nitrogen nucleus should consist of seven protons and seven neutrons. The mass of a nitrogen nucleus is fourteen mass units (seven protons and seven neutrons), while the atomic number equals seven (the charge of the nucleus is seven). In this case also the new hypothesis assumes an even number of particles in the nitrogen nucleus, which agrees with the value of its spin.

The idea of nuclei consisting of protons and neutrons, which was first expressed by the Soviet scientist D. D. Ivanenko, is in good agreement with known experimental data and is at present generally accepted.

If the charge of the nucleus is Z, and the mass number A, there should be in the nucleus Z protons and $A-Z$ neutrons, that is, the atomic number of the isotope is determined by the number of protons in the nucleus, while the mass number is the sum total of protons and neutrons.

So nuclei consist of protons and neutrons. Of course, the reader is right in saying: Well and good, suppose nuclei are made up of protons and neutrons, but then what about the electrons and positrons that appear both in artificial nuclear transformation and in those of naturally radioactive substances? Where do these particles come from if the nuclei themselves don't contain them? The question is quite justified. Didn't we often speak of "positrons ejected from nuclei" or "electrons emerging from nuclei" in our descriptions of nuclear transformations? And now we find that there are no electrons and positrons in nuclei.

Well, that *is* the case. There are no positrons and electrons in nuclei. They are formed in the space surrounding the nucleus from the excess energy generated in the nucleus as a result of the transformation which it undergoes.

We already know that positrons and electrons are not immutable structures. We also know that they can appear if sufficient energy is expended on their formation. It is this sufficient energy that is present in nuclear transformations.

Electrons and positrons do not exist in nuclei but result from nuclear transformations. In this sense, positron emission is very similar to the emission of light quanta by atoms. We are well aware of the fact that there are no light quanta inside an atom. But we are not surprised that the excess energy of an excited atom is converted into another form of energy, light energy. In the same way, we should not be surprised by excess energy in an atomic nucleus passing into another form of energy that is associated with the mass of an electron.

What happens in the nucleus itself when an electron or positron originates? Didn't we state earlier that when an electron flies out of a nucleus, the nuclear charge increases by unity, and when a positron shoots out it decreases by unity? This means that some sort of processes occurring in the nucleus are related to the appearance of a positron and electron. To figure this out let us examine some radioactive transformations.

Example 1. "Radionitrogen" converts into the isotope carbon-13. The transformation scheme is as follows:

$$_{7}N^{13*} \longrightarrow {}_{6}C^{13} + {}_{+1}e^{0} \text{ (positron)}.$$

How does the initial nucleus, radionitrogen, differ from the carbon-13 nucleus produced in the transformation. Both nuclei have the same mass number, thirteen, therefore, the total number of protons and neutrons in both nuclei is the same. But the charges of these nuclei differ: radionitrogen has a charge of seven, while that of carbon-13 is six. This means that *radionitrogen has seven protons and six neutrons, while a carbon-13 nucleus has six protons and seven neutrons.* The nucleus of radionitrogen has one proton more and one neutron less than the carbon nucleus, so that to obtain a carbon-13 nucleus from a nucleus of radionitrogen one must substitute the extra proton in the latter by a neutron. Summarizing, we come to the conclusion that the essence of the nuclear transformation, "radionitrogen converts into carbon," consists in *one of the seven nitrogen protons converting into a neutron.* It is in such a transformation (the nuclear charge in this act is actually reduced by unity) that a positron is produced near the nucleus at the expense of the surplus energy formed.

Example 2. "Radiosodium" transforms into magnesium-24. The transformation scheme is:

$$_{11}Na^{24*} \longrightarrow {}_{12}Mg^{24} + {}_{-1}e^{0} \text{ (electron)}.$$

In what way does the initial nucleus of radiosodium differ from the magnesium-24 nucleus that is formed in the transformation. The mass number of both nuclei is the same. Therefore, both nuclei have the same sum total of protons and neutrons. But the charges of these nuclei are not the same. The charge of a nucleus of radiosodium is eleven, while that of a nucleus of magnesium-24 is twelve. This means that a nucleus of radiosodium consists of eleven protons and thirteen neutrons while a magnesium nucleus has twelve protons and twelve neutrons. The radiosodium nucleus has one neutron more than the magnesium-24 nucleus. But the latter has one extra proton. So to obtain a magnesium-24 nucleus from radiosodium one has to replace the extra neutron by a proton. Our conclusion then is that the transformation of a nucleus of radiosodium consists in *one of the neutrons of radiosodium converting into a proton*, which results in the formation of a nucleus of magnesium-24. Resulting from this transformation is a free electron that appears in the space around the nucleus.

Thus the appearance of positrons and electrons is something like a signal that inside the nucleus certain component particles are in the process of transformation. The appearance of an electron is a sign that one of the neutrons within the nucleus has converted into a proton.

This transformation may be written down as follows:

$$_{0}n^{1} \longrightarrow {}_{1}H^{1} + {}_{-1}e^{0}.$$

The appearance of a positron means just the opposite, that a proton has converted into a neutron. This transformation may be written as:

$$_{1}H^{1} \longrightarrow {}_{0}n^{1} + {}_{+1}e^{0}.$$

Thus protons and neutrons inside the nucleus are capable of mutual transformation. Of course, attempts were made both with respect to protons and neutrons to represent them as eternal and immutable. But this lasted for only a very short time. Physicists were rather quick to see that

like the atomic nuclei themselves, these elementary particles are not unchangeable. Protons and neutrons can transform one into the other, and so in this sense we may speak of particles (say protons) vanishing, and of other particles (neutrons) appearing in their place.

It is of course possible to consider the proton and the neutron different states of one and the same particle. This is sometimes done, and the particle is called a "nucleon," which means nuclear particle. If this picture is accepted, one may speak of a proton as one of the possible nucleon states and a neutron as the other possible nucleon state.

The Radioactivity of the Neutron

And so a nuclear particle can exist either in a state called a "proton," or a state called a "neutron." In *nuclei* there can take place a transition of a particle from one state into another. The natural question is: Cannot such transformations happen to particles *in the free state*? Is it possible to observe directly the transition of a proton into a neutron or a neutron into a proton?

To answer this question let us compare the masses of the particles concerned:

$$\text{proton mass } m_p = 1.00758$$
$$\text{neutron mass } m_n = 1.00893$$

This comparison shows that the mass of a neutron is greater than that of a proton. Let it be added that the mass of a positron is likewise different from zero and equal to 0.00055 unit of atomic mass. This comparison shows that the mass (and energy) of a neutron and positron is more than the mass (and energy) of the proton

$$(m_n + m_e - m_p)\,c^2 = 1.8 \text{ million electron-volts.}$$

This is the reason why a proton cannot "of itself" convert into a neutron and a positron. Such a transformation requires that an energy of 1.8 million electron-volts be communicated to the proton.

In a nucleus that possesses excess energy, a proton can, by interaction with other nuclear particles, acquire an

energy sufficient for transformation into a neutron. However, in the free state a proton cannot find this energy, the result being that the transformation of free protons into neutrons does not occur. Protons (the nuclei of hydrogen atoms) prove to be stable

The situation for neutrons is quite different. The mass of a neutron is more than that of a proton; it is even more than the combined masses of a proton and an electron.

This means that in the transformation

$$_0n^1 \longrightarrow {}_1H^1 + {}_{-1}e^0$$

energy should be released (about 800,000 electron-volts). Thus, we see that the *spontaneous* transformation of a free neutron into a proton is possible. The surplus energy produced in such a transformation is taken up by electrons, which should appear with an energy of 800,000 electron-volts.

The spontaneous conversion of a neutron into a proton is not only possible but is inevitable, for we know that a system that possesses excess energy tends towards a state in which its energy is a minimum. In this respect there is complete parallelism between the conversion of a neutron into a proton and, for example, that of radiosodium into magnesium-24. In both cases the neutron vanishes, giving birth to a proton and a high-energy electron. It is therefore to be expected that these two processes should develop along similar lines. But the conversion process of radiosodium into magnesium-24 is of the nature of a radioactive transformation. For this reason, the transformation of a neutron into a proton should proceed by the same laws. Thus, free neutrons that do not exist in nuclei must be radioactive. But it is no easy matter to observe this sort of radioactivity.

We may recall that in the free state neutrons exist for only a very short time. A neutron "freed" from a nucleus continues in its motion until it encounters another nucleus and is absorbed by the latter. Owing to this fact we are able to observe it in the free state only en route from the nucleus that released it to the nucleus that absorbed it. Even if the neutron is slowed down to thermal velocities ($\sim 2 \times 10^5$ cm./sec. at room temperature), the time during

which the neutron's behaviour may be studied will be a mere 10^{-4} sec.

In this 10^{-4} sec., during which the neutron covers a distance of about 20 cm., we must succeed in detecting its radioactive disintegration. We are, of course, aware of the fact that radioactive decay does not involve all the radioactive particles simultaneously, but gradually. The probability of such a transformation is determined (see p. 43) by the magnitude of the decay constant. Out of a total quantity of N_0 radioactive nuclei, λN_0 nuclei decay in one second; here λ is the constant of radioactive decay.

It is one thing, of course, if the constant of radioactive decay of neutrons is a sufficiently large quantity: then the number of neutrons decaying during the transit time of their free path will be appreciable and it will be possible to detect their decay by experiment. However, if the λ of the neutrons does not prove to be a large quantity, then the number of neutrons that decay during 10^{-4} sec. (equal to $10^{-4}\ \lambda N_0$) will be so small that it will be impossible to detect neutron radioactive decay.

To detect the radioactive decay of neutrons, even when λ is not too small, requires a beam of neutrons of high intensity. But we already know that the number of neutrons produced in the process of nuclear transformations is very small. Up until recently it was practically impossible to create a neutron source producing from 10^8 to 10^9 neutrons per second. This was why we did not observe neutron radioactivity. It was only with the appearance of nuclear reactors, or piles, (to be discussed in a later chapter) which produce tremendous numbers of neutrons (more than 10^{12} per sec.), that radioactive decay of neutrons was observed in 1950. Neutrons were found to decay with a half-life of about 13 minutes. During 13 minutes, one half of the neutrons in a free state disintegrate into protons. The electrons that are produced in this decay possess a continuous energy-spectrum of a form similar to that of the beta spectra of radioactive substances.

The discovery of neutron radioactivity was of great scientific importance. The radioactivity of neutrons is direct confirmation of the hypothesis discussed above which states that radioactive beta decay and decay accompanied by the

emission of positrons (and also *K*-capture) are the result of transformations taking place inside nuclei, of transformations of neutrons into protons (beta decay) or protonsinto neutrons (positron decay, *K*-capture).

At the same time, the established fact of the conversion of a neutron into a proton, together with other transformations described earlier (the transformation of a gamma quantum into a positron and electron, of an electron and positron into gamma quanta, of a meson into an electron or positron, and the transformations of mesons of one mass into mesons of another mass) serve as a remarkable illustration of the principle of dialectical materialism concerning the mutual transformability of different forms of matter.

Nuclear Forces

Let us return to the question of radioactive transformations occurring in atomic nuclei.

Why does a nucleon pass from a "proton" state to a "neutron" state, or vice versa? How and when does this occur?

An examination of the forces that act between the nuclear particles will help us to understand this better. What can we say about the forces that act between particles within nuclei? Obviously, since nuclei contain charged particles, protons, there should exist, between the latter, electric forces. And since the sign of the charge of all protons is the same, and like charges repel, the forces acting between the protons should be forces of repulsion. If there were no other forces acting between the particles of nuclei, the latter would not be able to retain a stable state, because the repelling protons would fly out in all directions.

But atomic nuclei exist, which means that some other forces (aside from electricity) act on the protons and that these forces are attractive and of a magnitude that exceeds that of the forces of repulsion.

What are these forces then? Up till now we have encountered in nature two types of forces: electrical and gravitational. It is obvious that the forces in question are not electric forces. And it is also clear that these forces are not gravi-

tational because the latter are negligibly small between such tiny masses as those of the proton and the neutron, and cannot play a part of any importance in nuclear phenomena.

Thus, we arrive at the inevitable conclusion that the forces acting between particles in atomic nuclei are specific, nuclear, forces that are something new. The idea of the specific nature of these forces was developed by the Soviet scientists I. E. Tamm and D. D. Ivanenko.

Between what particles do these specific forces act? Are they forces that interact only between protons and neutrons or do they also act between other particles, such as two neutrons or two protons? How do these forces vary with the distance between the particles? What is their size?

It was found that at short distances (of the order of 10^{-13} cm.) nuclear forces are very great. They are much greater than the forces of repulsion acting between charged particles (protons) at the same distance.

Nuclear forces diminish with distance so rapidly that at a distance of 2 to 3×10^{-13} cm. they are practically zero.

This circumstance sharply distinguishes nuclear forces from electrical forces which obey Coulomb's law, so familiar from the school course of physics.

Electrical forces act over distances that greatly exceed the size of the nucleus, and for this reason no matter how many charged particles there are in the nucleus, each of them acts on all the others, and all the other charged particles act on each individual charged particle. In other words, the electrical forces act between all charged particles in the nucleus.

Quite different is the behaviour of nuclear forces. Since they diminish very rapidly with distance, their action does not extend to all particles in the nucleus, but only to adjacent particles. And what is more, there is a specific feature of nuclear forces that is concerned with the number of interacting neighbouring particles. In this respect, nuclear forces resemble the forces that determine the chemical properties of a substance. Like chemical forces, nuclear forces possess "valence," that is, the most stable structures are those with a definite number of interacting particles.

The greatest forces exist between a system of four particles, two protons and two neutrons. This peculiarity

of nuclear forces leads to the fact, well substantiated by experiment, that alpha particles, which consist of just such a number of protons and neutrons, are extraordinarily stable formations and that the most stable nuclei are those with an equal number of neutrons and protons. With the number of protons equal to the number of neutrons, the energy of the nucleus will be a minimum. If we built a nucleus with a slightly different ratio of particles, for example, with one less neutron (the number of neutrons would equal $n-1$) and one extra proton (the number of protons would equal $n+1$), the energy of such a nucleus would be greater than the energy of a nucleus that contains the same number of particles ($2n$), but composed of an equal number of protons and neutrons. Since any system tends to pass into a state of least energy, the first of these nuclei (consisting of $n+1$ protons and $n-1$ neutrons) will strive to convert into the second, which consists of n protons and n neutrons.

How should this transformation take place? Obviously, what is needed is for one proton to convert into a neutron. As we already know, this transformation will be accompanied by the ejection of a positron, resulting in positron radioactive decay. Such is the consequence that follows from the nature of the action of nuclear forces. Positron radioactive decay should be observed in nuclei with the number of neutrons less than that of protons. And true enough, positron decay is found in cases where there are fewer neutrons than protons, as witness ${}_6C^{10*}$, an isotope of carbon. This isotope is radioactive; it decays with the emission of a positron. The ${}_6C^{10*}$ nucleus has four neutrons and six protons. By decay it is transformed into a stable nucleus of ${}_5B^{10}$, which contains 5 neutrons and 5 protons. The nucleus of the ${}_8O^{14}$ isotope of oxygen has 6 neutrons and 8 protons. It decays by positron emission into a ${}_7N^{14}$ nucleus (a stable isotope of nitrogen). The ${}_7N^{14}$ nucleus contains 7 protons and 7 neutrons. Summarizing, then, if a nucleus contains more protons than neutrons, it is unstable and experiences positron radioactive decay.

On the other hand, nuclei with an excess of neutrons will also be unstable. They will undergo radioactive beta decay accompanied by the emission of electrons. For exam-

ple, a $_{9}F^{20}$ nucleus contains 11 neutrons and 9 protons. It decays with electron emission and is converted into $_{10}Ne^{20}$ (a stable neon isotope), the nuclei of which contain 10 neutrons and 10 protons.

Whether there occurs transformation of one type of nucleus (with a given number of protons and neutrons) into another type of nucleus (with a different number of protons and neutrons) depends above all on the relationships between the energies of these nuclei. In the case of light elements, the least energy is possessed by nuclei with the number of neutrons and protons equal.

In the total energy balance of the nucleus, it is not only the energy due to the action of these specific nuclear forces that is of importance; a part is also played by the energy of the electrical forces of repulsion between the protons that comprise the nucleus. The number of protons will increase along with the growth of the total number of nuclear particles. The importance of the repulsive forces of the protons will progressively increase. Now, nuclei with the same number of protons and neutrons will no longer be the most stable types. More stable will be those nuclei with the number of neutrons slightly in excess of the number of protons. For example, the nucleus of the only stable isotope of rhodium $_{45}Rh^{103}$ contains 58 neutrons and only 45 protons, in other words, the ratio between the number of neutrons and the number of protons is no longer unity, but has become 1.29. The nucleus of the only stable isotope of bismuth $_{83}Bi^{209}$ contains 126 neutrons and only 83 protons. The ratio here of the number of neutrons to the number of protons is 1.52. The higher the atomic number of the substance, that is, the greater the number of protons in the nucleus, the greater the surplus of neutrons necessary to make the nucleus stable.

Let us once again return to the question: Between what particles do nuclear forces act?

It was believed at first that the specific nuclear forces act only between unlike particles, that is, only between protons and neutrons. However, it was established by direct experiments based on the study of collisions of fast protons with hydrogen nuclei that the specific nuclear forces also act between two protons.

A study of the scattering of fast neutrons by deuterons and protons made it possible to establish that nuclear forces also act between two neutrons. Therefore, at present it is believed that nuclear forces act between all the particles that make up nuclei.

A Model of the Nucleus

How are the component particles of a nucleus arranged within the latter?

This question was answered independently by the Soviet physicist Y. I. Frenkel and the Danish physicist Niels Bohr. On their theory, nuclear structure is fundamentally different from the structure of atoms. In the atom we have a nucleus with a large charge and a large mass (the centre of the system) and electrons that surround the nucleus. In the atomic nucleus there is no such centre. Although the component particles, protons and neutrons, are not identical, they are to a certain degree equivalent, because the forces acting between all nuclear particles are approximately equal. And what is more, the forces acting between nuclear particles are extremely great. For this reason, all the particles in the nucleus will tend to arrange themselves as closely as possible to each other.

This is an exact analogy to what we find in the case of a drop of liquid. All the molecules of the drop are identical and the forces acting among them are the same. Under the action of these forces the liquid drop tends to take on a form that corresponds to a minimum of energy. This form is a sphere. The analogy between a liquid drop and a nucleus proved to be exceedingly profound; in many respects the behaviour of atomic nuclei resembles that of a charged liquid drop. Just as in a liquid drop, the particles of the nucleus interact with one another and exchange energy. If the forces of interaction between nuclear particles were not so great, we should be able to observe a phenomenon similar to the evaporation of a liquid. It is well known that evaporation of a liquid is due to the fact that one of the molecules accidentally acquires an energy large enough to overcome the attraction of the other molecules. Nuclear particles do not

usually evaporate because they have to overcome too great an attraction. However, if we "heat up" the nucleus, that is, if we impart to it additional energy, a somewhat similar evaporation may take place: one of the particles shoots out of the nucleus. To have this take place, the nucleus must be heated to thousands of millions of degrees.

How is it possible to heat the nucleus to such an extent?

Let us bombard the nucleus with a fast particle, a proton, a neutron, or an alpha particle. What will happen when such a particle penetrates the nucleus? On entering the nu-

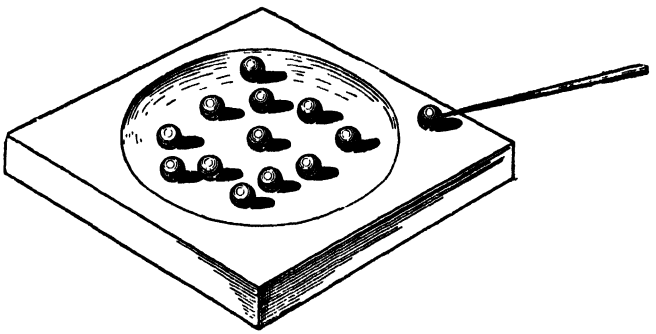


Fig. 48. Model of nuclear transformations.

cleus, it will immediately begin to interact with the other particles producing an exchange of energy. Once within the nucleus, this particle will fritter away its energy and will be unable to leave the nucleus. This is very well illustrated by the mechanical model shown in Fig. 48. There are a lot of tiny balls in the depression. What will happen if we push in another ball? Of course, if the depression were empty and there were no friction between the ball and the walls of the depression, our ball would very quickly roll out of it. But if the depression is filled up with balls, our ball will find it hard to get through. It will encounter the other balls and will communicate to them a part of its energy, and, finally, it will have so little energy left that it will not be able to leave the depression. After the ball enters the depression there will develop a chaotic move-

ment among the balls there. If there were no friction between the balls and the walls of the depression, some one of the balls would finally accumulate a considerable energy and would jump out. But this could be any one of the balls and not necessarily the one we pushed in.

The very same thing occurs in the nucleus. The incident particle imparts its energy to all particles within the nucleus. This energy is distributed between all the particles more or less evenly. The movement of the particles will become chaotic, and their kinetic energy will be greater. In this sense we may use the term "heating" the nucleus.

The penetration of a particle into the nucleus will have two consequences:

1) a new nucleus will be formed that contains one particle more than the original one;

2) the new nucleus will have excess energy brought in by the new particle. The nucleus will be excited, "heated" to thousands of millions of degrees (the average energy of thermal agitation of the particles of the nucleus at a temperature of one thousand million degrees is approximately equal to 0.1 million electron-volts).

Such a "heated" nucleus may exhibit the phenomenon of "evaporation." The excess energy or a considerable fraction of it may in time concentrate in some one particle and this particle will "evaporate;" it will leave the nucleus. And what will happen is what we call nuclear transformation. This event is well illustrated in Fig. 49.

Now what particle can evaporate? Let us assume that a high-energy neutron has entered the nucleus. The surplus energy in the newly formed nucleus may concentrate, for example, in one of the protons, and a proton will shoot out of the nucleus. The transformation will be of the type:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{12}Mg^{27} + {}_1H^1$$

According to the model under consideration, this transformation will be executed in two stages. During the first stage there will be formed a compound nucleus with the captured particle:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{13}Al^{28*}.$$

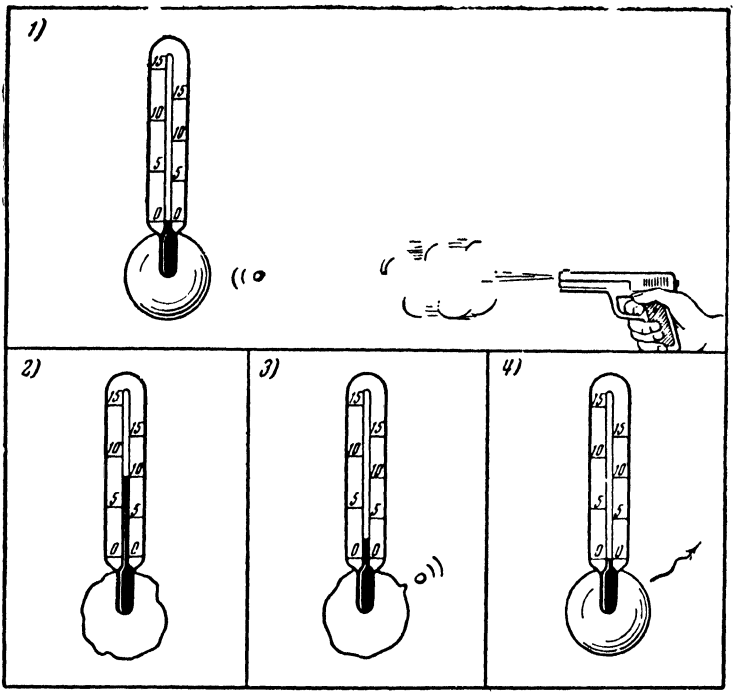


Fig. 49. Bohr-Frenkel model of nuclear excitation.

1 — a "nucleus" with a double-scale thermometer. The left-hand scale is divided into sections of 10,000 million degrees; the right-hand one, into millions of electron-volts. A neutron is "fired" into the nucleus; *2* — the neutron has entered the nucleus. The "nuclear drop" has heated up to a temperature of 80,000 million degrees (10 million electron-volts). All particles in the nucleus are excited. The drop is in a state of oscillatory motion; *3* — one particle has "evaporated." The temperature of the nucleus falls; *4* — the "nucleus" has emitted a gamma-ray quantum and has passed to the ground state.

This compound nucleus is "overheated," it has excess energy which goes to one of the protons. And the second stage of the transformation begins. With this extra energy, the proton evaporates from the nucleus:

$$_{13}Al^{28*} \longrightarrow {}_{1}H^{1} + {}_{12}Mg^{27}$$

The excess energy may be distributed in a group of particles consisting of two protons and two electrons. The

group will then be "evaporated" as a whole. In this case, we shall speak of an alpha particle being ejected:

$$_{13}Al^{27} + _0n^1 \longrightarrow _{13}Al^{28*} \longrightarrow _{11}Na^{24} + _2He^4.$$

It may also happen that one of the neutrons has concentrated a considerable part of the energy. Then a neutron will be ejected from the nucleus. Again we have the original nucleus, but still in an excited state. If the excitation energy is great, another particle may "evaporate," for example, one more neutron, and the type of transformation will be as follows:

$$_{35}Br^{79} + _0n^1 \longrightarrow _{35}Br^{80*} \longrightarrow _{35}Br^{78} + 2_0n^1.$$

Such transformations have been observed in experiments in the bombardment of nuclei with neutrons of energy greater than 10 million electron-volts. If, however, after the ejection of one of the particles of the nucleus there remains a small excess energy, it is usually released in the form of a gamma-ray quantum.

Finally, it may happen that a gamma quantum is emitted before the excess energy is taken up by one of the particles; after emission of the gamma-ray quantum, the remaining excitation energy of the nucleus will not be sufficient to eject any other particle, and the neutron that entered the nucleus will remain there. The particle will be captured.

$$_{13}Al^{27} + _0n^1 \longrightarrow _{13}Al^{28} + \text{gamma quantum}$$

Which of these competing processes will occur, the ejection of a particle or the ejection of a gamma quantum? If the neutron that entered the nucleus has brought a small amount of energy (a slow neutron), the probability that one of the nuclear particles will accumulate an excess energy sufficient to fly out will be small. One will have to wait a long time for such an event. The gamma quantum will emerge first. For this reason, the bombardment of a nucleus with slow neutrons usually results in neutron capture.

If the bombardment is done with neutrons possessing high kinetic energy, a great deal of excess energy will be

imparted to the nucleus. The probability that one of the nuclear particles will have energy enough to get out of the nucleus will be considerable. In this case the principal event will be the ejection of a particle. In some nuclei protons will escape, in others neutrons, and in still others, alpha particles. We will witness different types of nuclear transformations.

Though the analogy between the nucleus and a liquid drop is a deep one, it has its limits. The exceedingly small dimensions of nuclei (with radii of 10^{-13} to 10^{-12} cm.), the tremendous density of electricity and mass in nuclei, the enormous forces of interaction between particles result in certain specific peculiarities, which cannot be accounted for by this model, but it still explains many aspects of different phenomena involving atomic nuclei.

Nuclear Transformations Accompanied by the Ejection of Several Particles

If the energy of a particle that enters a nucleus is great, of the order of 100 million electron-volts, the nucleus will receive so much energy, it will heat up to such a high temperature that not one particle but several may "evaporate." If an energy of the order of one thousand million electron-volts were communicated to a nucleus, it would "evaporate" entirely, that is, all the particles composing it would fly out in different directions. Experiments carried out with deuterons and alpha particles of energy up to 200 and 400 million electron-volts respectively testify to the possibility of such processes. In these experiments, a large number of particles are found to be ejected from the nucleus. The number of emerging particles depends on the energy of the bombarding particle. Thus, in the bombardment of silver with alpha particles it has been established that a neutron emerges only when the energy of the alpha particle exceeds 11 million electron-volts. Obviously, the alpha particles require such a big energy in order to overcome the forces of repulsion that act between the alpha particles and the silver nucleus, and to penetrate into the nucleus. However, if the energy of the alpha particle exceeds 15 million elec-

tron-volts, cases are observed of two neutrons emerging from the nucleus. And when the energy of the alpha particle reaches 23 million electron-volts, three neutrons are observed to emerge.

Similar phenomena are observed when a deuteron is used as the bombarding particle. By way of illustration let us examine the transformations observed in the bombardment of nuclei with deuterons of energy 20 to 40 million electron-volts:

$$_{57}La^{139} + {}_{1}D^{2} \longrightarrow {}_{58}Ce^{141*} \longrightarrow {}_{58}Ce^{137} + 4{}_{0}n^{1},$$
$$_{51}Sb^{121} + {}_{1}D^{2} \longrightarrow {}_{52}Te^{123*} \longrightarrow {}_{52}Te^{119} + 4{}_{0}n^{1}.$$

In deuteron bombardment with particle energies of 50 million electron-volts, transformations have been detected that are the result of evaporations from the compound nucleus of five neutrons, for example:

$$_{51}Sb^{121} + {}_{1}D^{2} \longrightarrow {}_{52}Te^{123*} \longrightarrow {}_{52}Te^{118} + 5{}_{0}n^{1},$$
$$_{45}Rh^{103} + {}_{1}D^{2} \longrightarrow {}_{46}Pd^{105*} \longrightarrow {}_{46}Pd^{100} + 5{}_{0}n^{1}.$$

Deuterons of energy 60 million electron-volts heat up a compound nucleus to such an extent that six neutrons can evaporate from it. An example of this is the transformation:

$$_{57}La^{139} + {}_{1}D^{2} \longrightarrow {}_{58}Ce^{141*} \longrightarrow {}_{58}Ce^{135} + 6{}_{0}n^{1}.$$

Transformations have been recorded which are the result of evaporation from the compound nucleus of a still greater number of particles. Thus, in the bombardment of uranium with high-energy deuterons, the following transformation is encountered:

$$_{92}U^{238} + {}_{1}D^{2} \longrightarrow {}_{93}Np^{240*} \longrightarrow {}_{93}Np^{231} + 9{}_{0}n^{1}.$$

The result of this transformation is a new element, neptunium, which we shall describe in detail later on.

In the bombardment of nuclei with particles of still higher energies, so many particles are ejected (evaporated) that it is no longer any easy matter to establish the exact nature of the ejected particles. Thus, for example, in the bombardment of antimony, which consists of two isotopes

with mass numbers 121 and 123, by deuterons of 180 million electron-volts, there were found isotopes of palladium-100 and 101, of silver-102, 103 and 104, and cadmium-105, 107 and 115.

How is it possible for the isotope palladium-101 to originate from antimony of mass 123 (or 121)?

This is possible only if both neutrons and charged particles with a total mass of 22 units (this is for a transformation of the antimony-123 isotope) and a charge of 15 units (the atomic number of palladium is 46) are ejected ("evaporate") from the nucleus. We do not yet know exactly how many particles are ejected in such a transformation and we are not able to state exactly what the particles are, but it is clear that there are very many of them and that the majority are neutrons. This conclusion may be made on the basis of two arguments:

1. The bombardment of nuclei by fast particles usually results in the emergence of many neutrons and a small number (1-2) of charged particles (protons or alpha particles). This is due to the fact that charged particles can leave a nucleus only if they possess considerable energy, while neutrons can leave even when the energy is small.

2. The antimony nucleus in question lost a large mass (22 units) and a comparatively (judging from the mass) small charge.

The formation of another isotope of palladium with mass number 100 corresponds to the ejection from the antimony of particles with a total mass of 23 and a charge of 5. The formation of isotopes of silver-102, 103, 104, obviously occurred as a result of particles with a total mass 21,20 and 19 and a charge of 4 leaving the nucleus of antimony-121. The formation of cadmium-105 is due to the ejection of particles with a total mass of 18 and a charge of 3. Cadmium-107 was obviously formed in the ejection of particles having a total mass of 16 and a charge of 3. A more definite conclusion concerning particles that are formed in such a transformation may be made for the isotope cadmium-115. The transformation involving the formation of this isotope is as follows:

$$_{51}Sb^{123} + {}_{1}D^{2} \longrightarrow {}_{52}Te^{125*} \longrightarrow {}_{48}Cd^{115} + 2\,{}_{2}He^{4} + 2\,{}_{0}n^{1}.$$

To summarize, then, when a deuteron (and also an alpha particle) of energy of the order of 200 million electron-volts enters a nucleus, it causes the evaporation of a large number of particles (the bulk are neutrons), among which a few are charged.

The appearance in such transformations of several charged particles has been confirmed by direct observations. In studying the tracks of such high-energy deuterons and alpha particles in the emulsions of photographic plates, it has been found that they form stars that resemble the stars produced by cosmic rays. Then stars consist of several tracks of charged particles. For example, some of them have four and five tracks. It is highly probable that deuterons and alpha particles possessing energies of a thousand million electron-volts are capable of causing the complete disintegration (evaporation) of a nucleus.

Chapter XI

NUCLEAR FISSION

Neutron Capture by Uranium

In this chapter the reader will learn about a recent discovery that is undoubtedly one of the outstanding achievements of mankind. And as is often the case, the search was for one thing, but something quite different was discovered. The beginning had to do with the nature of the so-called "transuranium elements." It is this. As follows from the facts detailed in Chapter VII, it is possible to make the majority of the chemical elements radioactive by irradiation with neutrons. If the radioactive transformation is accompanied by the emission of an electron (beta decay), the result will be an element one unit further in the Periodic Table than the one irradiated.

The Mendeleyev Periodic Table consists of 92 elements, with the last place occupied by uranium. And so Fermi decided to try irradiating uranium with neutrons. He wanted to see whether a new element would be produced, one that should occupy a place after uranium, that is element No. 93, which had not hitherto been encountered in nature. Such an element would itself probably be radioactive, otherwise we would have discovered it among the stable elements. The disintegration of its nuclei would probably provide just as rich and interesting a picture of nuclear transformations as does the radioactive decay of uranium nuclei. It is also possible that as a result of several transformations there might be formed an element with a still larger atomic number, for instance, 94.

It might be that these transformations would disclose to us the properties of elements hitherto unknown on the earth and would lift the veil from the secret of the limited number of chemical elements; and maybe we would learn

why it is that uranium is the last element of the periodic system. It was these interesting speculations that led Fermi to subject uranium to neutron irradiation.

The experiment was a success. After irradiation, Fermi found that uranium exhibited a new radioactive radiation that had never before been observed. This radiation consisted of a rather complex set of beta rays.

An analysis of the curve of diminishing intensity of the new radiation was enough to establish the presence of four half-lives, namely: 10 seconds, 40 seconds, 13 minutes, and finally, 90 minutes. In addition to these four half-lives, at least one more still longer half-life could be surmised.

We know very well that the presence of each individual half-life in the radiation corresponds to the presence of a definite radioactive isotope in the composition of the radiating substance. It will be recalled that uranium has only three isotopes:

$$_{92}U^{238*},\ _{92}U^{235*},\ _{92}U^{234*}$$

The relative abundance of the latter two isotopes is extremely small. $_{92}U^{235*}$ makes up 1/140 of $_{92}U^{238*}$, and the portion of $_{92}U^{234*}$ comes to 1/17,000. So the presence, in the beta radiation of uranium subjected to neutron bombardment, of five, or possibly more half-lives showed at once that we were dealing with a complex phenomenon. And true enough, it was no easy matter to disentangle this phenomenon. Five years of work by the biggest authorities on radioactivity was necessary to clarify the problem.

Assuming that at least one of the observed half-lives belongs to element No. 93, Fermi attempted to identify it assuming that by virtue of the basic regularities of the periodic system, element No. 93 is a chemical analogue of the elements of manganese and rhenium, with which it should occupy the same vertical column in the table. Without dwelling on the details of the complete and complex chemical procedure, we may note that from the data obtained it followed that not a single one of the elements, from 86 to 92 inclusive, could be radioactive with a half-life from 13 to 90 minutes. The only thing left to assume, and this Fermi did, was that the beta radiation he had discovered came from an element with an atomic number 93 or more.

This element was produced by the beta decay of uranium upon the capture of a neutron.

This discovery provoked a tremendous interest among scientists. Many of them questioned the uniqueness of Fermi's conclusions. In their opinion, the chemical manipulations he had performed allowed for another interpretation. It was soon demonstrated experimentally that protactinium possesses chemical properties similar to those found by Fermi for a 13-minute activity. Fermi's conclusions began to seem doubtful. Thus arose the problem of the "transuranium elements" (that is, elements that follow uranuim in the periodic system) that attracted the attention of many investigators.

An Investigation of the Nature of the Transuranium Elements

After a detailed study of the transuranium elements, Hahn, Meitner and Strassmann soon became convinced that the problem was much more complicated than was at first supposed by Fermi. The curve of intensity attenuation of radioactive radiation appeared different at different times of observation. The impression was that certain radioactive substances arise not during the irradiation but some time afterwards. If this proved correct, it would mean that the new substances are formed not during neutron irradiation of uranium but later, as a result of radioactive transformations, and therefore that there is a chain of radioactive transformations.

The thorough analysis of the intensity-attenuation curve of radioactive radiation carried out by Hahn, Meitner and Strassmann confirmed this assumption, and the outcome of a long series of investigations was the following schemes of transformations involving uranium subjected to neutron irradiation:

1. ${}_{92}U + {}_{0}n^{1} \longrightarrow {}_{92}U^{*}$ (10 sec.) $\longrightarrow {}_{93}$Eka Re* (2.2 min.) $\longrightarrow$
$\longrightarrow {}_{94}$Eka Os* (59 min.) $\longrightarrow {}_{95}$Eka Ir* (66 hr.) $\longrightarrow$
$\longrightarrow {}_{96}$Eka Pt* (45 hr.) $\longrightarrow {}_{97}$Eka Au (nonradioactive),
2. ${}_{92}U + {}_{0}n^{1} \longrightarrow {}_{92}U^{*}$ (40 sec.) $\longrightarrow {}_{93}$Eka Re* (16 min.) $\longrightarrow$
$\longrightarrow {}_{94}$Eka Os* (5.7 hr.) $\longrightarrow {}_{95}$Eka Ir (nonradioactive),
3. ${}_{93}U + {}_{0}n^{1} \longrightarrow {}_{92}U^{*}$ (23 min.) $\longrightarrow {}_{93}$Eka Re (nonradioactive).

In the schemes describing the transformations of uranium, Hahn and Strassmann suggested denoting the symbols of the then unknown elements which should occupy places following uranium in the Periodic Table, by the prefix Eka (which means "following"). Thus they suggested calling element No. 93 eka-rhenium Eka Re (which means following rhenium in the vertical column of the Periodic Table); element 94, eka-osmium (Eka Os); element No. 95, eka-iridium (Eka Ir), etc. Enclosed in parentheses to the right of the symbol of the element is the value of the half-life of the given radioactive isotopes.

As may be seen from the accompanying schemes, uranium irradiated by neutrons is involved in an amazing chain of successive radioactive transformations. The initial members of this chain with half-lives of 10 sec. and 40 sec. were firmly established by direct chemical means after long and painstaking efforts. The 2.2-min. half-life proved to be a daughter of 10-sec. activity. The 16-min. half-life was the daughter of 40-sec. activity. By varying the neutron irradiation time of uranium one could prove conclusively the connection between these half-lives. A similar relation has been established for the following sections of these radioactive branches.

Subsequent studies of the chemical properties of radioactive substances having the half-lives indicated in these schemes seemed to confirm the mutual connection between the half-lives that had been found. The only thing to point out is that the half-lives of 13 and 90 minutes found by Fermi have been replaced by more exact values, which according to Meitner are 16 and 59 minutes respectively. Besides, a large number of half-lives were discovered that Fermi had not noticed, especially those of longer duration. Their total reached nine, and the highest atomic number of the newly discovered transuranium elements reached 97.

In the transformation scheme of the transuranium elements proposed by Hahn, Meitner and Strassmann, there are three parallel series of radioactive transformations. But why three? Could it be that they correspond to three different isotopes of the initial uranium product? Maybe one series is formed by uranium-238, the other by uranium-235, and the third by uranium-234. But intensity measure-

ments of the radiations did not permit attributing the detected half-lives to the rare $_{92}U^{235}$ isotope, and all the more so to the $_{92}U^{234}$ isotope. And so one had to conclude that all the foregoing transformation series involve the single $_{92}U^{238}$ isotope of uranium. This circumstance was quite naturally bewildering. Although the connection between the different radioactive products that appear and decay after neutron irradiation of uranium was firmly established, and although it seemed that the explanation given by Hahn and Meitner was the only one possible, there still arose many puzzling questions, as for instance:

1. If it is true that all of the established daughter products originated from the isotope $_{92}U^{238}$, then the transuranium elements should possess isomeric states. It seemed strange that three isomeric states are formed at once.

2. It was not clear what the nature of such isomerism could be.

3. Why is it that the capture of one neutron by uranium creates such a high degree of instability that as many as five beta decays are required to obtain a stable product? And is this product indeed stable? It seemed very strange that elements with an atomic number of 95 or 97 could be stable.

The Discovery of Rare-Earth Elements Among the Decay Products of Uranium

Soon new questions were added to the above three.

While investigating, by means of the filtration method, the half-lives of the radioactive disintegrations of uranium irradiated by neutrons, Joliot-Curie and Savitch found, in addition to the half-lives of 40 sec., 2.2 min. and 16 min. noted earlier in the work of Hahn, Meitner and Strassmann, a new period of 3.5 hr. An nvestigation of its chemical properties showed them that the bearer of this activity is an analogue of the rare-earth lanthanum. And so they surmised that the radioactive isotope of actinium (the analogue of lanthanum) is the unknown radioactive emitter of 3.5 hr.-half-life. However, they soon noticed an exceedingly strange thing. The 3.5-hour substance could be separated chemically from actinium, but would not be separated from lanthanum. From these facts it followed that the 3. 5-hour

radioactive product is not an isotope of actinium, as was originally suggested by Joliot-Curie and Savitch, but rather an isotope of lanthanum. Jolio-Curie and Savitch actually discovered the fission of uranium but they did not grasp the true significance of their discovery.

Hahn and Strassmann repeated the work of Joliot-Curie and Savitch slightly extending the programme of investigations. Among the decay products of uranium they sought not only for analogues of lanthanum, but also for radioactive substances that are analogues of barium. They succeeded in establishing the fact that three radioactive substances behave like barium: one with a half-life of 25 min., a second with a half-life of 110 min., and a third with an inaccurately measured half-life of several days. These initial substances gave rise to daughter substances that were also radioactive. Chemically, these daughter products behaved similarily to lanthanum (which in the Periodic Table follows barium). Just as Joliot-Curie and Savitch, Hahn and Strassmann at first thought that they were observing only the analogues of barium and lanthanum, and that in fact the radioactive isotopes of radium $_{88}$Ra and actinium $_{89}$Ac (in the Periodic Table radium is located in the same vertical column as barium, while actinium is located with lanthanum, therefore the chemical properties of radium and barium, and also lanthanum and actinium are similar) were radioactive emitters. However, they too were soon convinced that the radioactive emitters formed in the transformation of uranium differ in their behaviour from radium and actinium. On the other hand, it was impossible, chemically, to distinguish them from the elements of barium and lanthanum.

In their paper, Hahn and Strassmann wrote as follows: "As chemists we are constrained to state definitely that the new substances (that is, the products of neutron capture by uranium) behave not as radium but as barium." Such was the unexpected result of the "hunt" for transuranium elements.

And now to the earlier mentioned unsolved problems we may add a new one.

4. How is it possible that the radioactive isotopes of the stable elements of barium and lanthanum, which, as we

know, are in the middle of the Periodic Table and not at the end, could be formed as a result of the beta transformations of uranium?

The Fission of Uranium

Lise Meitner was the first to unravel this problem. She assumed that the transformation of uranium which has captured a neutron does not proceed in the manner of ordinary radioactive substances. This transformation is not connected with the ejection from the excited nucleus either of beta particles or alpha particles. The absence of the latter in the transformation of uranium was proved by control experiments. According to Meitner, an excited uranium nucleus produced by the penetration into it of a neutron splits into two lighter nuclei; *in the act, the charge and mass of the nucleus split into two nearly equal halves.* The barium and lanthanum detected by Hahn and Strassmann are two such fragments of uranium.

The hypothesis of the division of a uranium nucleus into two fragments was a peculiar solution to the problem of the transuranium elements. The analogues of rhenium, osmium, iridium and other elements (eka-rhenium, eka-osmium, eka-iridium) are by no means elements heavier than uranium. Actually, these elements proved to be technetium (element No. 43, an analogue of rhenium that comes before and not after rhenium in the Periodic Table), ruthenium (element No. 44, an analogue of osmium, which comes before osmium in the Periodic Table), rhodium (element No. 45, an analogue of iridium), that is, elements that are nearly half as heavy as uranium. Apparently, the group of uranium fragments is composed of the radioactive isotopes of just these elements.

A little further on we shall discuss in more detail what is formed in the fission of uranium. For the present we shall focus the attention of the reader on the causes that lead to the fission of uranium nuclei.

Let us return to our analogy with the charged liquid-drop. It is known that a drop retains its shape by the forces of surface tension. A charge communicated to the drop

results in repulsive forces developing between the different parts of the drop that have the same charge. If this charge is large enough, the forces of repulsion between the two parts of the drop will be so great that the surface tension will no longer be able to counteract them and the drop will

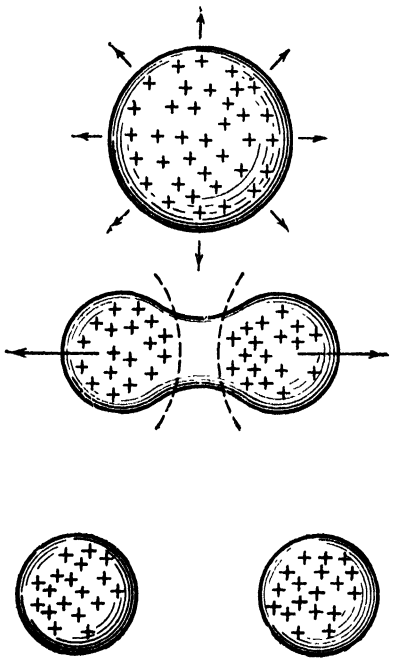


Fig. 50. How a nuclear drop divides.

break into two parts. Fig. 50 illustrates the division of a liquid drop. First it elongates forming a waist, and then the drop separates into two parts.

Something very similar happens to a heavy nucleus. As the charge of the nucleus increases, the action of the electrical forces of repulsion begins to dominate over the action of the attractive forces. The nucleus becomes unstable and breaks into two parts. Estimates show that when

Z is greater than 100, the repulsive forces will begin to overpower the attractive forces.

Nuclear fission may occur even with a smaller Z if the nucleus is excited, that is, if we endow it with additional energy. In each of the fragments that are formed in the fission of an unstable nucleus, the attractive forces will now be greater than the forces of repulsion and the energy of the system will be much less than what it was originally. Therefore, it is to be expected that a tremendous amount of energy will be released in the formation of two fragments.

The theory of nuclear fission was developed by Y. I. Frenkel, and Bohr and Wheeler.

Chemical Elements with Atomic Numbers Above 92

As soon as the hypothesis of nuclear fission was announced, a fever of work began in the physics laboratories. An indication of the intensity of this work is that over one hundred scientific papers devoted to nuclear fission were published in less than a year. Such intensive investigations had never before been conducted in any branch of physics. Within a short period of time, a study was made of the basic features of nuclear fission, and the extraordinary significance of this discovery became apparent. But let us first finish with the question of what is formed as a result of the capture of a neutron by uranium.

We have already related that barium and lanthanum are found among the elements formed in the fission of uranium. Soon radioactive yttrium and strontium were found among the fragments. In the immediate vicinity of uranium the air was found to contain the radioactive isotopes of krypton and xenon. Subsequently, isotopes of bromine, rubidium, molybdenum, antimony, tellurium, iodine, cesium and other elements were found.

A big piece of work was done by V. G. Khlopin and his pupils in establishing the nature of the fragments. All these fragments turned out to be isotopes of elements in the middle of the Periodic Table. Interest in these elements was quite natural if we bear in mind the nuclear fission hypothesis. But we would like to give an answer to the ques-

tion which we posed at the very beginning and which naturally arises in the mind of the reader: Do these transuranium elements really exist after all?

The discovery of fission showed the original explanation of the results of neutron irradiation of uranium to be incorrect. The elements believed at first to be transuranium elements were in fact something else, yet this was not proof that transuranium elements do not exist. Subsequent studies showed that such elements do exist. Element No. 93 is really produced in the bombardment of uranium by neutrons. It is formed in the beta decay of uranium-239 with a half-life of 2.3 days. Consequently, the mass number of this isotope of element No. 93 is 239.

An interesting experiment confirming the formation of element No. 93 is described on page 318. Element No. 93 was called neptunium after the name of the planet Neptune which is next farthest from the sun after Uranus.

Another isotope of neptunium $_{93}Np^{237}$ (Np is the chemical symbol of neptunium) was discovered in 1942. Neptunium-237 decays with the emission of alpha particles. $_{93}Np^{237}$ has a half-life of 2.2×10^6 years. At present, the known isotopes of neptunium are those with mass numbers of 231, and 233 through 239. They are all radioactive. The longest-lived isotope of neptunium (mass number 237) is the representative of element No. 93 in the Periodic Table.

The next element after neptunium, element No. 94, was discovered at the end of 1940. An isotope of this element with a mass number of 238 was produced in the radioactive decay of neptunium-238, which emits beta rays and has a half-life of 2.0 days. Element No. 94 was called plutonium after the name of the planet next after Neptune.

The most important isotope of plutonium (chemical symbol Pu) is $_{94}Pu^{239}$, which is formed from $_{92}U^{239}$ by beta decay. $_{94}Pu^{239}$ has a half-life of 23,600 years and decays by the emission of alpha particles.

Besides these isotopes, plutonium has isotopes of mass numbers 232, 234 through 237, 241 and 242. Many of these isotopes have rather long half-lives, as, for instance, that of plutonium-240 with 6,580 years. Plutonium-238 has a half-life of 89 years, plutonium-241 a half-life of 10 years, while the half-life of plutonium-236 is 2.7 years.

Plutonium-242 has the longest half-life, approximately one million years. Being the longest-lived isotope, plutonium-242 is the representative of element No. 94. Plutonium-242 decays with the emission of an alpha particle and converts into uranium-238.

Neptunium and plutonium are not the only elements with atomic numbers greater than uranium. The bombardment of uranium and plutonium with high-energy alpha particles (up to 40 million electron-volts) accelerated in a cyclotron revealed elements with the atomic numbers of 95 and 96 called respectively americium (chemical symbol Am) and curium (Cm). These elements have already been found to have several isotopes, for example, americium has eight ($_{95}Am^{237}$, $_{95}Am^{238}$, $_{95}Am^{239}$, $_{95}Am^{240}$, $_{95}Am^{241}$, $_{95}Am^{242}$, $_{95}Am^{243}$, $_{95}Am^{244}$), curium seven ($_{96}Cm^{238}$, $_{96}Cm^{240}$, $_{96}Cm^{241}$, $_{96}Cm^{242}$, $_{96}Cm^{243}$, $_{96}Cm^{244}$, $_{96}Cm^{245}$). And among these isotopes there are some relatively long-lived ones.

Thus, the isotope americium-241 has a half-life of 490 years, while americium-243 has a half-life close to 7,600 years. This is the longest-lived isotope of americium.

The isotope curium-243 has a half-life of 35 years, the half-life of curium-244 is 19 years, while that of curium-245 is 20,000 years.

The radioactive isotopes of elements with atomic numbers 97 and 98 were obtained in 1950. These elements were named berkelium (with its chemical symbol Bk) and californium (Cf). Berkelium is at present known to have three isotopes: $_{97}Bk^{243}$, $_{97}Bk^{245}$, $_{97}Bk^{249}$. The half-life of $_{97}Bk^{249}$ is approximately one year. Californium has still more isotopes: $_{98}Cf^{244}$, $_{98}Cf^{246}$, $_{98}Cf^{248}$, $_{98}Cf^{249}$, $_{98}Cf^{250}$, $_{98}Cf^{251}$, $_{98}Cf^{252}$, $_{98}Cf^{253}$. Californium-249 has a half-life approximately equal to 500 years.

All the transuranium elements are produced by bombardment (with neutrons or alpha particles) first of uranium, then of plutonium, americium, curium, berkelium and californium. Such bombardments have already yielded isotopes of element No. 99 [which was named einsteinium (E) in honour of A. Einstein] with mass numbers 252, 253, 254 and 255. The existence of an element with an atomic number of 100 has been established [fermium (Fm) in honour of E. Fermi]. This element has isotopes with mass numbers

254, 255, 256. In 1955, Seaborg and co-workers announced the production of a radioactive isotope of element No. 101 with a mass number of 256. This isotope was obtained by bombarding an isotope of element No. 99 (mass number 253) with alpha particles. For element No. 101, Seaborg suggested the name "mendelevium" (Mv) in honour of the distinguished Russian scientist D. I. Mendeleyev.

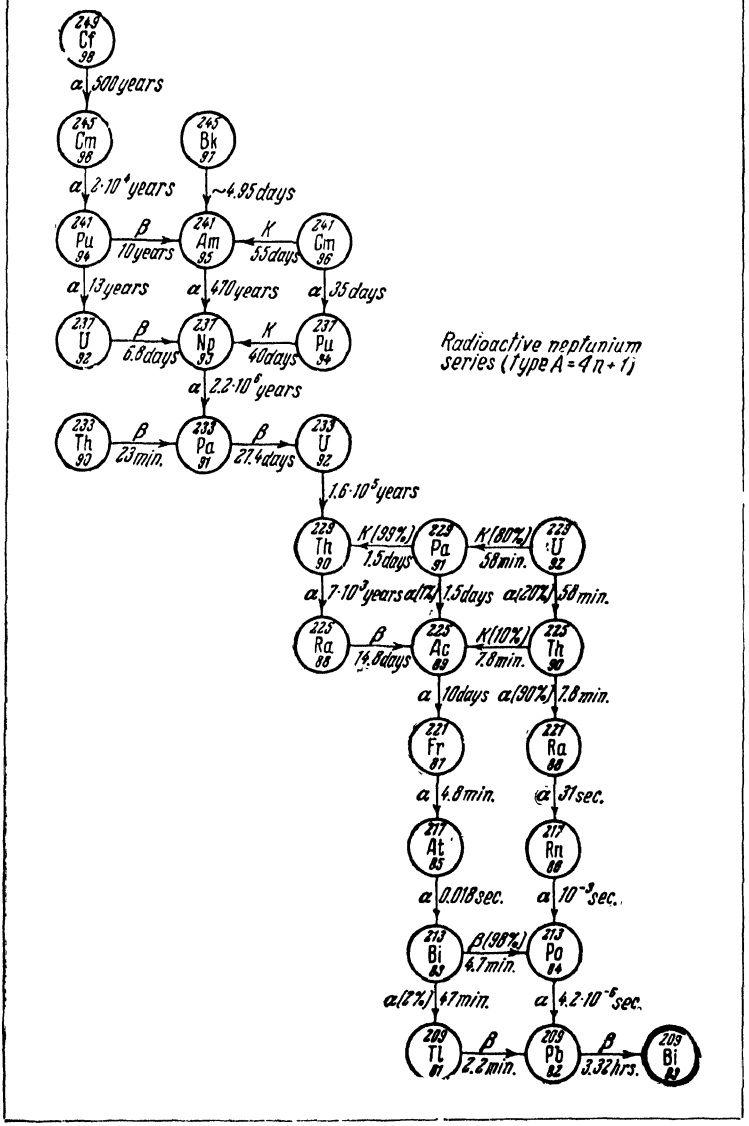
In 1957 a group of Swedish and American scientists announced the discovery of an isotope of element No. 102—"Nobelium" (No).

It is interesting to note that the new transuranium elements form a group similar to the group of rare earths. The first element of this group is actinium, and for this reason the group of transuranium elements (together with thorium and uranium) received the name of "actinides."

The identified transuranium elements proved to be unstable, as one could have expected, the decay forming a series of radioactive transformations analogous to the transformations in the series of the naturally radioactive elements. It is noteworthy that the transuranium elements form a new radioactive family of the type $4n+1$. What does this mean?

Earlier, attention was drawn to the fact that among the naturally radioactive elements there were isotopes whose mass numbers are divisible by 4, that is, may be represented by the formula $A=4n$. Such, for example, are the members of the thorium series. The isotopes of the uranium series have slightly different mass numbers, namely: their mass number A is expressed by the formula $A=4n+2$, where n is an integer (for example, for ${}_{92}U^{238}$ $n=59$, for ${}_{88}Ra^{226}$ $n=56$). The isotopes of the actinium series have mass numbers expressed by the formula $A=4n+3$, where n is integer. Scientists had long since been wondering at the lack of such isotopes among the naturally radioactive types whose mass number could be expressed by the formula $A=4n+1$, and now it was found that such isotopes exist among the transuranium elements. Table VII gives a scheme of the radioactive series $A=4n+1$ called the neptunium series.

It is interesting to note that this series has several parents, not one. Thus, ${}_{94}Pu^{241}$ forms the foregoing radioactive



Radioactive neptunium series (type $A = 4n + 1$)

series; $_{92}U^{237}$, which is obtained from $_{92}U^{238}$ by the reaction $(n, 2n)$, that is, a nuclear reaction in which a neutron enters a nucleus of uranium and knocks out two neutrons, may also be considered as the parent of this family (series). Thorium can be the initial product for the formation of this series. Neutron irradiation of thorium produces the radioactive isotope $_{90}Th^{233}$, which is a beta emitter. After two successive beta emissions we get $_{92}U^{233}$, which is a member of the neptunium series. Curium-241, californium-249, and berkelium-245 may be considered parents of this family or series. The remarkable thing in the radioactive series of neptunium, shown in Table VII, is the presence in it of side branches. Thus, for example, in addition to the main branch

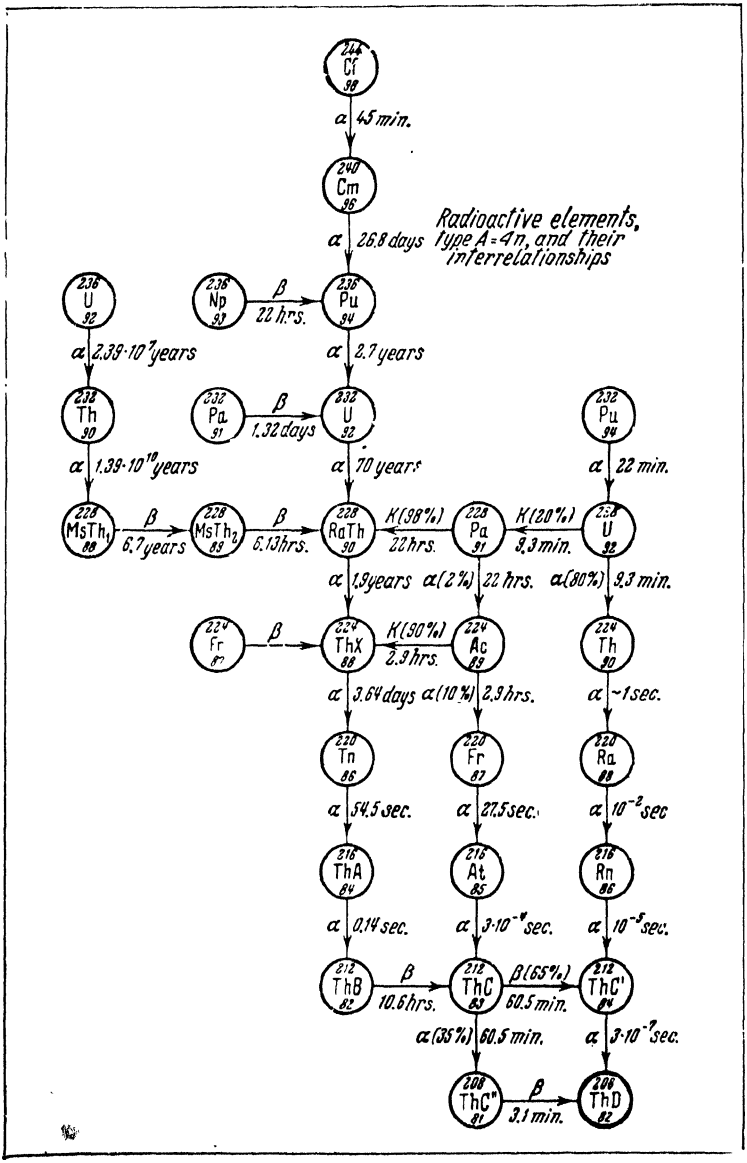
$$_{91}Pa^{229} \longrightarrow {}_{89}Ac^{225} \longrightarrow {}_{87}Fr^{221} \longrightarrow {}_{85}At^{217} \longrightarrow {}_{83}Bi^{213} \longrightarrow {}_{81}Tl^{209}$$

there exists another branch

$$_{92}U^{229} \longrightarrow {}_{90}Th^{225} \longrightarrow {}_{88}Ra^{221} \longrightarrow {}_{86}Rn^{217} \longrightarrow {}_{84}Po^{213} \longrightarrow {}_{82}Pb^{209}.$$

The fact that in the radioactive series of neptunium there are no elements with such long half-lives as uranium and thorium have explains why they are not observed in nature.

The investigation of the transuranium elements made it possible not only to discover the existence of a new radioactive neptunium series; it greatly extended our knowledge of the radioactive series $A=4n$, $A=4n+2$, and $A=4n+3$. It turned out that the natural radioactive series shown in Tables I-III(pp. 52-54) are only parts of the corresponding radioactive series, which are really much richer and have a large number of parents (just like the neptunium series) and many side branches. A complete picture of the radioactive isotopes that make up the thorium, uranium and actinium series, and their mutual transformations are given in Tables VIII, IX, and X. Properly speaking, they can no longer be called series of uranium and actinium, because the transformations begin with larger atomic numbers (berkelium, californium and einsteinium). As may be seen from these tables, the radioactive families have become so numerous and with so many branches that the picturesque expression "radioactive family" and all the more so "radio-


Radioactive elements, type A=4n, and their interrelationships
244 Cf 98
α 45 min.
240 Cm 96
α 26.8 days
236 U 92
236 Np 93
β 22 hrs.
236 Pu 94
α 2.39·10⁷ years
α 2.7 years
232 Th 90
232 Pa 91
β 1.32 days
232 U 92
232 Pu 94
α 1.39·10¹⁰ years
α 70 years
α 22 min.
228 MsTh1 88
β 6.7 years
228 MsTh2 89
β 6.13 hrs.
228 RaTh 90
K(38%) 22 hrs.
228 Pa 91
K(20%) 3.3 min.
228 U 92
α 1.9 years
α(2%) 22 hrs.
α(80%) 3.3 min.
224 Fr 87
β
224 ThX 88
K(90%) 2.9 hrs.
224 Ac 89
224 Th 90
α 3.64 days
α(10%) 2.9 hrs.
α ~1 sec.
220 Tn 86
220 Fr 87
220 Ra 88
α 54.5 sec.
α 27.5 sec.
α 10⁻² sec
216 ThA 84
216 At 85
216 Rn 86
α 0.14 sec.
α 3·10⁻⁴ sec.
α 10⁻⁵ sec.
212 ThB 82
β 10.6 hrs.
212 ThC 83
β(65%) 60.5 min.
212 ThC' 84
α(35%) 60.5 min.
α 3·10⁻⁷ sec.
208 ThC'' 81
β 3.1 min.
208 ThD 82

active series" are no longer applicable, it would seem more appropriate to use the phrases "radioactive clan" or "radioactive race." This is why we called Table VIII "Radioactive Elements of the Type $A=4n$ and Their Interrelationships." The captions to Tables IX and X are similar.

In these tables we see examples of very interesting branches. Thus, for example, (Table IX) $_{94}Pu^{234}$ decays in two different ways: some nuclei decay by emission of an alpha particle and convert into an isotope of uranium-230, while the others, by means of *K*-capture, transform into the isotope neptunium-234. Both nuclei, $_{92}U^{230}$ and $_{93}Np^{234}$, undergo many diverse transformations which ultimately lead to a single element $_{84}Ra^{214}C'$. Here are the transformations that correspond to this long branch:

$$_{94}Pu^{234} \longrightarrow {}_{92}U^{230} \longrightarrow {}_{90}Th^{226} \longrightarrow {}_{88}Ra^{222} \longrightarrow {}_{86}Rn^{218} \longrightarrow {}_{84}Ra^{214}C';$$

the other branch of transformations is still more complex:

$$_{94}Pu^{234} \longrightarrow {}_{93}Np^{234} \longrightarrow {}_{92}UII^{234} \longrightarrow {}_{90}Io^{230} \longrightarrow {}_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} \longrightarrow$$
$$\longrightarrow {}_{84}Ra^{218}A \longrightarrow {}_{82}Ra^{214}B \longrightarrow {}_{83}Ra^{214}C \longrightarrow {}_{84}Ra^{214}C'.$$

Nuclear Fragments and Their Energy

The appearance among the transformation products of uranium, of isotopes of bromine, krypton, barium and lanthanum was an indication that uranium had split into two parts. Nearly all the elements of the middle part of the Periodic Table have been found among the fragments of uranium fission. It is curious to note that among these isotopes there are some whose mass numbers are much higher than the mass numbers of stable isotopes. Thus, for example, the heaviest stable isotope of tellurium has a mass number of 130, whereas tellurium isotopes of mass numbers 131, 132, 133, 134 and 135 have been found among the fragments. The stable isotope of iodine has a mass number of 127, whereas iodine isotopes with mass numbers from 129 through 137 are found among the fission fragments. Such heavy isotopes cannot be formed by the transformation of stable nuclei, and if there were no nuclear fission we would not be able to learn about the properties of such nuclei.

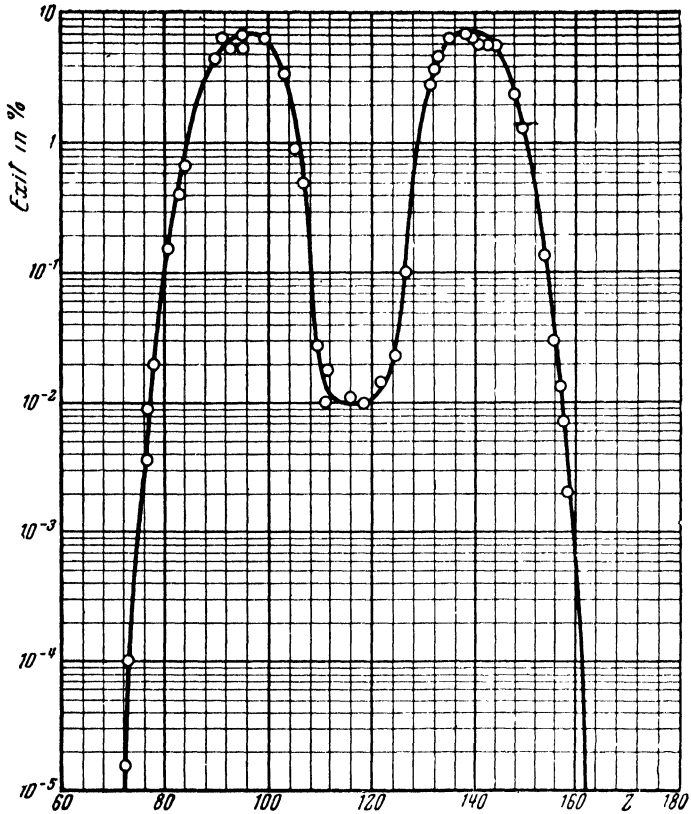


Fig. 51. Distribution curve of the mass numbers of fragments.

Of course, not all fragments occur with the same frequency. Fig. 51 shows a curve describing the probability of fission of a nucleus of uranium-235 into different fragments. Here, the percentage content (on a logarithmic scale) of the fragments is shown as a function of the mass numbers of the fragments.

This curve shows that among the fragments there are isotopes with mass numbers ranging from 72 to 160. The most frequently encountered fragments of the fission of

uranium-235 are those of mass number 90 through 100 and from 135 to 145. The curve in Fig. 51 permits dividing the fragments into two groups: "light fragments" and "heavy fragments." A curious fact is that fragments with mass numbers 116 through 120 are rarely encountered. Such fragments comprise a minimum in the curve in Fig. 51. This means that uranium-235 exceedingly rarely splits into two equal parts. The probability of such fission is of the order of 10^{-4}. Uranium-235 usually fissions into two unequal fragments—one heavy fragment and one light one.

The break-up of uranium into two fragments is the most frequently encountered fission process. However, cases have been recorded of uranium splitting into three fragments, and sometimes even four fragments.

We pointed out earlier that the fragments produced in uranium fission must possess a high energy. But how great is this energy and how is one to measure it?

Obviously, if the fragments have a large energy, then despite their considerable mass they will have a high initial speed and, consequently, will be able to cover a perceptible distance in air. In its motion the fragment will ionize tens of times more heavily than an alpha particle.

Joliot-Curie, Fermi and a number of other investigators had already found that the fragments produced during fission can traverse a considerable distance in matter. Joliot-Curie discovered this in the following way. He collected fragments emerging from uranium into a bakelite plate located close to the uranium. The method used by Joliot to determine whether uranium fission fragments impinged on the plate was to examine the radioactive transformations of the fragments that had got stuck in the plate. The nonradioactive plate very soon became radioactive when it was brought close to the uranium.

The fact that fragments have a considerable range may be observed in cloud-chamber pictures. Fig. XL in the Appendix shows such a photograph which clearly exhibits the tracks of fragments produced in the fission of uranium. To obtain this photograph, a large grid with a thin film containing uranium oxide was placed aross the chamber and then irradiated with neutrons. Uranium fission was produced as a result of irradiation. The fragments produced

formed two long tracks which are clearly visible on the right-hand side of the photograph. The large number of other, shorter tracks that are seen in this picture originated in the collisions of neutrons with atoms (more correctly, with the nuclei) of hydrogen, which is a constituent of the vapours that fill the cloud chamber.

While observing the fragments that impinge on the plate, Joliot-Curie noticed that they hit the plate even when the latter is not directly on the uranium, but at a certain distance from it, or if a thin cellophane foil is placed between the plate and the uranium.

This enabled a very interesting experiment to be performed. Indeed, if fragments are capable of traversing a certain layer of matter, then by taking a layer of uranium so thin that all the fragments produced leave it, we will no longer detect in it, after bombardment, radioactivity created by fragments. The radioactivity of such a layer will be due only to those substances that are produced without the fission of uranium, that is, by neutron capture if the uranium is irradiated by slow neutrons. Consequently, this will result in uranium-239 and its decay products, that is, the transuranium elements. This experiment confirmed the formation of uranium-239 and its subsequent decay products.

Joliot's experiments showed that fragments are capable of travelling up to 2.1 cm. in air and that, consequently, they possess considerable energy. An important problem arose, that of measuring the energy of the fragments. The chief difficulty was that uranium itself is radioactive and emits alpha rays. The fragments likewise undergo radioactive transformations. Each such transformation produces beta particles of high energy. It was no easy matter to extricate oneself from this maze of difficulties and to find a reliable way of separating the fragments from other rays that appear in the transformation of uranium.

But the way was found. Use was made of the fact that fragments whose charge reaches 20 units ionize far more copiously than do electrons and alpha rays. A tiny ionization chamber connected with a powerful amplifier that permitted direct measurement of the ionization current produced in the chamber by an entrant particle was designed.

By tuning the amplifier to various degrees of amplification, it was possible to achieve a situation in which the unit as a whole did not respond when an alpha particle (to say nothing, of course, of the action of electrons) entered the ionization chamber. However, when a particle entered the ionization chamber producing ionization many times greater than that of alpha particles, the ionization current was amplified to an easily discernible magnitude.

Measurements carried out with this apparatus showed that when uranium was placed alongside such an ionization chamber, neutron irradiation of the uranium produced current pulses that corresponded to the entrance into the ionization chamber of a strongly ionizing particle. The magnitude of the pulses indicated that the ionizing capacity of the fragments was tens of times greater than that of alpha particles. This is the reason why it was possible to register nuclear fragments on the background of alpha and beta particles. If the amplifier, which amplifies the current in the ionization chamber, is made proportional, that is, such that the output current is proportional to the current in the ionization chamber, and, besides, if the size of the ionization chamber is such that a fragment in it can be completely decelerated, then it is possible to determine the energy of the fragment. Indeed, by determining the current intensity at the output of the amplifier and knowing the amplification factor, we can ascertain the current intensity in the ionization chamber. The latter is determined from the number of ions which the fragment produces over its range. Knowing the number of ions and also the fact that the production of one ion pair requires an energy of 33 electron-volts, it is easy to calculate the energy of the fragment.

Careful measurements show that the energy of a fragment is tremendous even by nuclear standards. The energy of different fragments proved slightly different, but still of the order of several tens of millions of electron-volts, with some fragments having a hundred million electron-volts. This figure seems still more spectacular when we recall that in the fission of uranium two fragments are produced and that each of these fragments is radioactive and undergoes a whole series of radioactive transformations. During

these transformations, a considerable energy equal to several tens of millions of electron-volts is released.

Below we give an approximate energy balance of the fission of a nucleus of uranium-235. Let us express the energy in units of mass. The total energy of fission is composed of the following parts:

mass of fragments (including neutrons)	234.8
mass of electrons produced in the radioactive decay of the fragments	0.005
kinetic energy of the fragments	0.172
radiation energy	0.023
Total	235

In its turn, the radiation energy is composed of the energy of gamma rays (about a fourth of the total quantity of radiated energy), the kinetic energy of electrons which make up another quarter of the total radiation energy, and the neutrino energy comprising nearly one half of the entire radiated energy.

These figures show that in the fission of a nucleus of uranium there is released a tremendous energy close to 200 million electron-volts.

Secondary Neutrons

The amount of energy released in the fission of uranium is amazing. This phenomenon is obviously one that is destined to play an outstanding role in the history of mankind and without doubt plays a part of first-rate importance in nature. However, the meaning of this figure—200,000,000 electron-volts per nuclear fission of uranium—was fully understood in the light of a new phenomenon that was soon to be discovered, that of the origin of secondary neutrons in the process of nuclear fission.

The essence of the matter is this. We know that the distinguishing feature of heavy nuclei is that the number of neutrons in them exceeds by far the number of protons. As an example, in the nucleus of the most abundant isotope of uranium, ${}_{92}U^{238}$, there are 92 protons and 146 neutrons,

which means that there are 1.6 neutrons to every proton. The ratio of protons to neutrons in elements in the middle of the Periodic Table is quite different. Bromine, for example, has 35 protons and only 45 neutrons, which gives a ratio of 1.3 neutrons per proton. Correlating the ratio of neutrons and protons in uranium and in bromine, we naturally arrive at the conclusion that there should be an excess of neutrons in the fragments produced during the fission of uranium.

By way of illustration let us assume that uranium-238 has split into two equal parts. Each of these parts will have a charge of 46 and a mass number of 119. A glance at the table of the isotopes of stable nuclei shows us that the atomic number of 46 corresponds to the element palladium. Palladium has several stable isotopes. The mass number of the heaviest of them is 110. Thus, in each of the halves of uranium there will be at least nine extra neutrons.

From the preceding chapter we know what should follow when there is a surplus of neutrons in the nucleus. One of the neutrons converts into a proton, and a free electron appears in the immediate vicinity of the nucleus. What occurs, consequently, is beta decay.

Of course, one beta decay will be insufficient for the excess neutrons within the fragment to vanish. In the concrete case of palladium, at least four beta transformations would be required for the palladium-119 isotope to convert to a stable isotope. Indeed, the element nearest palladium with a mass number of 119 is tin. The atomic number of tin is 50, therefore, four beta transformations will be needed for the transformation of palladium-119 into tin-119. In these transformations, four neutrons will be converted into four protons. This illustration explains why the fragments produced in uranium fission undergo a whole series of successive beta transformations: they are the result of a large excess of neutrons in the fragments produced during fission.

It is true that uranium usually splits into two unequal parts; the usual division is into two slightly different fragments with mass numbers about 140 and 100. This, however, does not change anything. The neutron surplus in the fragments is considerable, and the fragments convert into stable

isotopes by a series of beta transformations. Thus, the distinguishing feature of the fragments produced is the surplus of neutrons in them.

A very natural question is: do all the excess neutrons really convert into protons? Doesn't it happen that in the process of fission a certain quantity of excess neutrons are outside the nuclei? This important problem was investigated by many workers including Flerov and Russinov of the U.S.S.R. And the answer was soon forthcoming. Yes, in nuclear fission there arise free, or, as they are called, secondary neutrons.

This discovery was of tremendous importance and will be discussed in its full value in the next chapter.

For the present let us examine some of the details of the formation of secondary neutrons.

Our primary interest will be to find out how many neutrons originate in fission. We know that in the fission of uranium different fragments are produced. This means that not all nuclei of uranium split in the same way: for this reason the number of secondary neutrons produced in the different modes of fission of uranium nuclei differ. However, an important point was to determine the mean number of secondary neutrons originating in the fission of one nucleus of uranium. What is the mean number of neutrons produced per fission of a uranium nucleus? This question was one that extremely interested scientists. However, to establish the exact number of neutrons produced on the average in the fission of uranium nuclei required extensive and painstaking work. And at last it was found that the mean number of neutrons produced per nuclear fission of uranium-235 is 2.5 ± 0.1 The fission of a plutonium-239 nucleus produces still more neutrons, the average being 3.0 ± 0.1. An essential factor was that the number of secondary neutrons proved greater than unity. If the average number of secondary neutrons produced per decay had been less than unity, the value of this discovery and interest in it would have been quite different. But seeing that the number of secondary neutrons was more than unity, the interest in this discovery was extraordinary.

Taking into account the origin of secondary neutrons in nuclear fission, the fission process may be depicted as

shown in Fig. 52 for the fission of plutonium-239 nuclei.

The investigation of secondary neutrons produced in the fission of nuclei permitted of establishing one more very interesting phenomenon of practical importance. It was found that if uranium is irradiated with neutrons and then the neutron source is removed, secondary neutrons continue to appear for a certain time. These neutrons ob-

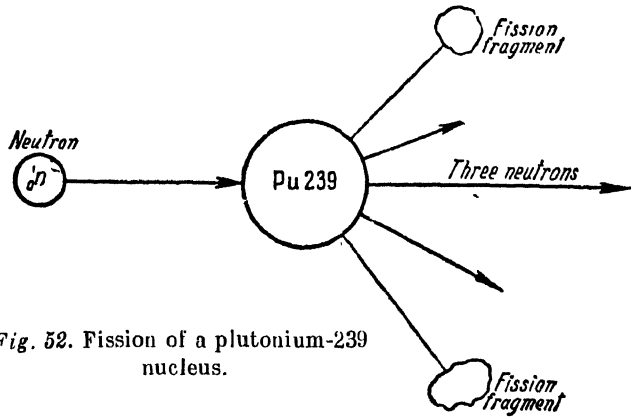


Fig. 52. Fission of a plutonium-239 nucleus.

served after irradiation of the uranium has ceased are called delayed neutrons. A detailed study of the phenomenon of delayed neutrons showed that 0.2 to 1 per cent of the neutrons produced in the fission of uranium are delayed by 0.1 second and 0.07 per cent of the neutrons are delayed by a minute. An intensive irradiation of uranium showed delayed neutrons 13 minutes after irradiation had ceased.

The reason for the appearance of delayed neutrons is clear. Delayed neutrons appear as a result of the formation (in the process of the radioactive transformations of fragments) of such nuclei as contain excess energy sufficient for the "evaporation" of neutrons. Since such nuclei originate as the result of a radioactive transformation, we observe neutrons for a certain period *after* the nucleus has split and fragments have been formed.

By way of illustration let us examine the transformation of a nucleus of $_{35}Br^{87}$. As may be seen from the dia-

gram in Fig. 53, this nucleus can disintegrate in three ways. And in all three types of decay a beta particle is ejected. However, the quantity of energy released in each type of decay differs. Consequently, the $_{36}Kr^{87}$ nuclei formed by the decay of $_{35}Br^{87}$ will have different supplies of energy. $_{36}Kr^{87}$ nuclei with the largest amount of energy radiate delayed neutrons and convert into $_{36}Kr^{86}$. The $_{36}Kr^{87}$ nuclei with the least energy are the normal non-excited state of the isotope krypton-87. There is not enough energy for evaporation of neutrons from such nuclei, just as from $_{36}Kr^{87}$ nuclei with intermediate energy (excited state), and therefore the transition

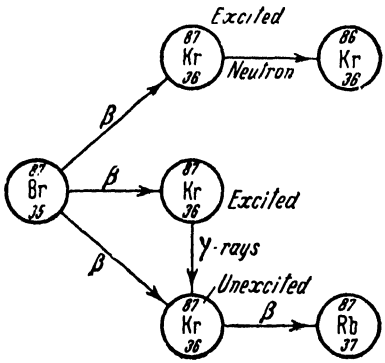


Fig. 53. The transformations of a nucleus of $_{35}Br^{87}$.

$$_{36}Kr^{87} \longrightarrow {}_{36}Kr^{86} + {}_{0}n^{1}$$

does not occur.

The isotope $_{36}Kr^{87}$, in the nonexcited state, is radioactive. It transforms into a stable isotope of $_{37}Rb^{87}$ by beta decay.

Thermal Neutrons and the Fission of Uranium

High-energy neutrons were used in the original uranium fission experiments. In this connection it was important to determine what neutron energies caused fission. For example, is there an energy limit for neutrons capable of initiating fission, or maybe a neutron of any energy, even the smallest, is capable of producing fission once it gets into a nucleus?

To answer this question one had first to find out how thermal neutrons act, whether they too are able to split uranium nuclei. As soon as the appropriate experiments were carried out it was immediately seen that thermal neu-

trons are capable of producing fission in uranium. And what is more they proved much more effective than fast neutrons. It may be noted that the foregoing figures on the average number of neutrons per fission of the nuclei of uranium-235 and plutonium-239 have to do precisely with the case of fission by thermal neutrons.

When it was established that thermal neutrons are capable of causing fission of uranium just like high-energy neutrons, and that, consequently, the important thing in fission is not the energy of the neutrons but the fact of penetration of the neutron into the nucleus, a new question arose. Uranium as we know, is not a homogeneous substance but a mixture of three isotopes, uranium-238, uranium-235 and uranium-234. Are all these nuclei fissionable, or maybe it is only one isotope that undergoes fission? To resolve this question, it was necessary to separate the uranium isotopes. This was done by means of a mass-spectrograph. The quantity of separated isotopes of uranium was very small: only 0.03 microgram of uranium-235 and four micrograms of uranium-238. But even this was sufficient to demonstrate that thermal neutrons split nuclei of uranium-235, while uranium-238, which makes up the bulk of the uranium, is not fissionable under the action of thermal neutrons. To get a full picture of uranium fission, one still had to determine the behaviour of the isotope uranium-238 when irradiated with fast neutrons. Experiments showed that uranium-238 nuclei are fissionable by fast neutrons.

The limit energy value at which fission of uranium-238 by neutrons begins was determined in the works of the Soviet physicists G. N. Flerov and K. A. Petrzhak. Their measurements indicate that uranium-238 is fissionable only by neutrons with energies in excess of one million electron-volts; neutrons with less energy are not capable of causing the fission of uranium-238.

What will happen if a lower-energy neutron penetrates into a nucleus of uranium-238? It will lead to the formation of a new radioactive isotope of uranium, uranium-239 which decays in the normal way with the emission of beta rays. The beta decay of this isotope leads to the formation of the transuranium elements of neptunium and plutonium.

To summarize, the isotopes of uranium-235 and uranium-

238 behave differently as regards fission. The nuclei of U-235 are fissionable both by slow and fast neutrons, those of U-238 only by neutrons of energy above one million electron-volts.

Speaking of observations of the fission of uranium isotopes, we have constantly referred to the fission of uranium-238 or uranium-235. But the fission process occurs when the neutron has penetrated into the nucleus. Consequently, we observe in fact the fission not of the nuclei of uranium-238 and 235, but of the nuclei of uranium-239 and 236, because after the capture of a neutron, uranium-235 becomes uranium-236, and uranium-238 becomes uranium-239.

The Spontaneous Fission of Uranium-235 Nuclei

Flerov and Petrzhak, the first to measure the required energy for fission of uranium-239, decided to study in more detail the behaviour of the uranium-235 isotope.

The fewer neutrons there are in the nucleus, the smaller the fraction of energy (due to the attractive forces of the nuclear particles) in the total energy of the nucleus. A uranium-236 nucleus has just as many protons as the isotopes of uranium-235 and 238, therefore, the action of the repulsive forces of the charges of all three nuclei is the same. But the number of neutrons in all three isotopes is different. This means that the role of the forces of attraction is likewise different. The isotope uranium-239 has the largest number of neutrons, hence its attractive forces will be greatest. This is the reason, as we know, why the nucleus of uranium-239 does not break up spontaneously; this nucleus requires an excess energy sufficient for fission. It is the fast neutron that carries such an excess of energy into the nucleus of uranium-238.

The isotope uranium-236 splits immediately after its formation. This means that the excess energy created in this nucleus during its formation (as a result of neutron capture by a nucleus of uranium-235) is of itself sufficient for fission to occur. Thus the action of attractive forces in a nucleus of uranium-236 is not much in excess of the action of the repulsive forces. The change in the ratio

between the forces of attraction and repulsion occurred because the uranium-236 nucleus has fewer neutrons than the uranium-239 nucleus.

Obviously, in uranium-235 nuclei with their smaller number of neutrons than uranium-236, the action of the forces of attraction will be still less in excess of the forces of repulsion. The question then naturally arises: cannot uranium-235 fission spontaneously, without any irradiation by neutrons? It might be expected that such fission occurs, but with a small probability. This means that the number of nuclei of uranium-235 undergoing fission at each instant is small, and for this reason such fission could remain undetected. It may be that the spontaneous fission of uranium-235 nuclei will be detected if special experiments are devised in conditions which permit the registration of a very small number of fragments.

Such experiments were carried out by Flerov and Petrzhak. They used a special ionization chamber with a large number of plates covered with uranium oxide. The total surface area occupied by the uranium oxide amounted to 1,000 sq. cm. This large area was needed to observe the appearance of fragments in the largest possible quantity of uranium. The ionization chamber was connected to an amplifier, just as in other similar arrangements for fragment investigation: however, the resolving power of the Flerov-Petrzhak amplifier was considerably greater than that of ordinary amplifiers because with the large surface area of uranium the number of alpha particles that entered the chamber was great, and it was necessary to eliminate superposition of ionization from several alpha particles simultaneously.

The Flerov-Petrzhak observations established the production of fragments of uranium not irradiated with neutrons. True, the number of such fragments was exceedingly insignificant, the total being only six cases of fission per hour. If account is taken of the quantity of uranium used in the experiment, the following conclusion may be drawn: if we consider that it was precisely the isotope uranium-235 that underwent fission, the time required for one half of the given quantity of uranium-235 to undergo fission will amount to 10^{14}-10^{15} years. That is how slowly the spontaneus fission of uranium occurs. However, it might be that

the assumption concerning the fission of uranium-235 only, is incorrect; for we know that the mixture of uranium isotopes contains the isotope uranium-234, whose nuclei contain still fewer neutrons than do those of uranium-235. It may be that the nuclei of this isotope are the ones that undergo fission. In this case the half-life will be slightly less: 10^{12} to 10^{13} years *.

The principal phenomena connected with nuclear fission were studied in uranium. However, the investigations should naturally show whether uranium is the only element whose nuclei are capable of fission, or whether there exist other substances possessing similar properties. Quite naturally, the first to be investigated were elements with the largest atomic numbers, because the nuclei of these elements contain the largest quantity of protons. And this means that these nuclei will exhibit the strongest forces of repulsion. It was therefore natural to expect fission to occur primarily in these elements. The search was rewarding. Thorium, ionium and protactinium exhibited fission, which was observed when these substances were subjected to irradiation by fast neutrons. Thermal neutrons were unable to cause fission of these nuclei.

Thus in thorium-233 fission is caused by neutrons of energy exceeding 1.7 million electron-volts. Protactinium-232 is fissionable under the action of neutrons of energies above 100,000 electron-volts. Neutrons with energies in excess of 1.2 million electron-volts cause fission of ionium. Nuclear fission may be produced not only by neutrons, but also by deuterons with energies above eight million electron-volts. It was likewise established that fission of bismuth, lead, tallium, platinum and tantalum occurs under the action of alpha particles of energy 400 million electron-volts and deuterons of energy 200 million electron-volts.

As for thermal neutrons, they are capable of initiating fission not only in uranium-235, but also in plutonium-239 and uranium-233, which is obtained by irradiation of thorium-232 by neutrons.

* At present there is evidence for spontaneous fission occurring in the case of uranium-238 nuclei also. The rate of this fission is very small: about 20 decays per hour per gram of uranium-238. The corresponding half-life is roughly 10^{17} years.

Chapter XII

NUCLEAR CHAIN REACTIONS

The Chain Reaction

In the preceding chapter we discussed the phenomenon of the fission of atomic nuclei. Two remarkable properties of this phenomenon at once became the focus of attention.

1) An enormous energy of 200 million electron-volts is released during the fission of each nucleus.

2) Nuclear fission is accompanied by the ejection of secondary neutrons. The number of these secondary neutrons produced during the fission of one nucleus is greater than unity.

The second property placed before scientists a problem of prime importance, that of creating a chain reaction.

Let us first analyze an ideal case. We assume that two new neutrons have been produced in the fission of a nucleus. Further we assume that each of the neutrons penetrates one of the uranium nuclei, causing fission.

What will happen if under such conditions one single primary neutron penetrates into a nucleus of uranium?

The nucleus will split in two and two new neutrons will be produced. These neutrons in their turn will be captured by the uranium nuclei, which will undergo fission and produce four new neutrons. These four will cause the fission of four uranium nuclei. And the result will now be eight neutrons. The number of neutrons and with them the number of fissionable nuclei will constantly increase.

The ideal case we have just considered is an accelerating chain reaction. The term "chain" applied to the foregoing transformation was taken from chemistry where a chain reaction is understood as such a reaction the products of which are able again to react with the initial products. The reaction thus continuously develops.

This is exactly what happens in our case. The neutron ejected in the fission of a uranium nucleus can penetrate into another uranium nucleus and, thus, again produce nuclear fission. The result is more neutrons, which again enter uranium nuclei and cause fission, etc. Thus is established a nuclear chain reaction.

Of course, the above-described ideal case differs greatly from what actually occurs. Everything is considerably more complicated.

First of all, not every neutron that penetrates a nucleus of uranium causes fission of this nucleus. We know, for example, that fission of uranium-238 nuclei is initiated by neutrons of energy not less than a million electron-volts. If the energy of the neutron is less, it will be absorbed by uranium-238 without causing any fission whatsoever. Out of 650 nuclei of uranium-235 that have captured thermal neutrons, only 549 (or 85 per cent) experience fission. For plutonium-239 this percentage is still lower: only 63 per cent of the nuclei that capture thermal neutrons are fissionable. The remaining nuclei undergo radioactive transformations which do not produce any free neutrons. For this reason, the development of a chain reaction is properly determined not by the average number of neutrons produced in nuclear fission, but by the "reproducibility" of the neutrons, that is, the number of neutrons produced in fissions related to a single neutron absorbed by a nucleus. The "reproducibility" of neutrons in the case of uranium-235 is higher than for plutonium-239, being 2.11 for the former and only 1.94 for the latter.

Second, we assumed that every neutron produced in fission would be captured by a uranium nucleus. But this is not so. We know very well that the probability of neutron capture by a nucleus is small. A neutron is capable of traversing considerable layers of matter before it is captured by a nucleus. The probability of neutron capture by a nucleus is the smaller, the greater the energy of the neutrons.

Since uranium will always occupy a certain definite and finite space, there will always be a certain quantity of neutrons that will leave the volume in which the uranium is located and will thus "leave the game."

Third, we assumed pure uranium for our ideal case.

But in reality it is difficult to obtain a pure substance; the latter will always contain some impurities. If there are many impurities or if they strongly absorb neutrons, then a substantial portion of the neutrons may be captured by the atomic nuclei of these impurities and will likewise be unable to maintain the nuclear fission process. For this reason, although the fission process produces more than one neutron, it was impossible to say beforehand whether a chain reaction would develop or not. The general picture of processes that occur in uranium under the action of neutrons is given in Fig. 54.

The problem was to understand all the complex phenomena influencing the development of a chain reaction and to determine the conditions in which it is possible.

There are three factors that impede the development of a chain reaction:

1) absorption by uranium-238 of slow neutrons, which is not accompanied by fission;

2) escape of neutrons through the surface of the uranium block to the outside;

3) the presence of impurities, especially those that tend strongly to absorb slow and "thermal" neutrons.

Why are impurities that absorb slow neutrons dangerous?

In the preceding chapter it was shown that nuclear fission is much more effectively produced by thermal neutrons than by fast neutrons. But thermal neutrons are effective only against uranium-235, and not at all against the isotope uranium-238.

However, the amount of the 235 isotope in uranium is 140 times less than the isotope of U-238, and yet the effect of thermal neutrons is so strongly felt as to exceed the action of fast neutrons on uranium-238 nuclei.

Thus, the principal role in uranium fission is played by thermal neutrons acting on uranium-235; they are the ones that will play the basic part in the development of a chain reaction. This is why impurities capable of absorbing slow and thermal neutrons are so dangerous.

If the part played by the slow and thermal neutrons is so great, it should be worthwhile converting all fast neutrons into slow neutrons. We know that neutrons may be slowed down by passing them through a thick enough layer of

light substances. Neutrons are most readily slowed down by hydrogen. If we mix a hydrogen-containing substance (water or paraffin) with uranium, the hydrogen in this

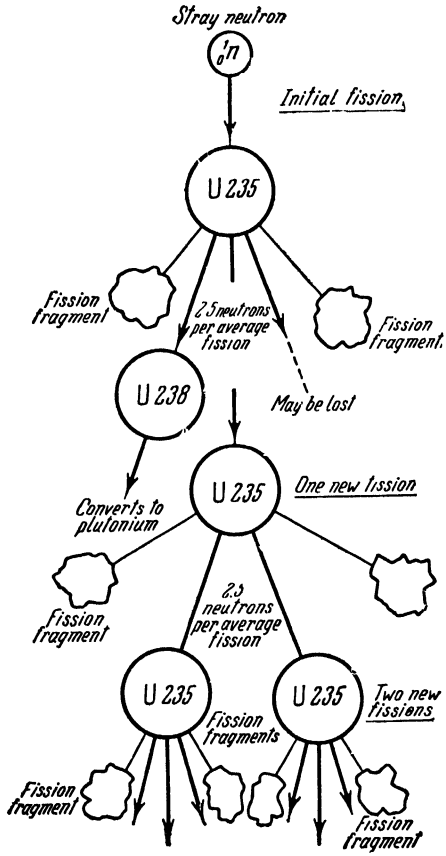


Fig. 54. The processes which occur in uranium when the latter is irradiated by neutrons.

mixture will slow down the neutrons. The slow neutrons will be absorbed by uranium-235 and will initiate fissions.

Let secondary neutrons be formed in the fission of one nucleus (for example, of uranium-235) initiated by the

capture of a thermal neutron. In the slowing-down process a part of the neutrons will disappear, they will be captured by the nuclei of uranium-238 and by different impurities, and a part will escape.

A certain fraction of the original number of neutrons will remain. Let us designate this fraction by the number p (p is a proper fraction; if in the slowing-down process, for example, one-third of the neutrons is absorbed, two-thirds will remain; in this case p will equal $\frac{2}{3}$). Then, of n neutrons produced in the fission of a nucleus, np neutrons will become thermal, while $n(1-p)$ will be lost in the slowing-down process.

But not all the moderated (slowed-down) neutrons will enter the nuclei of uranium-235. Some of them will be captured by the uranium-238 or by impurities, which include nuclei of the moderator, a substance that decelerates neutrons (in this case fission does not occur), and only a certain number of slow neutrons will enter the nuclei of uranium-235 to initiate fission.* Let the portion of such cases comprise the number k.

Summarizing, then, of the initial n neutrons produced in the fission of uranium, only npk neutrons will initiate secondary fission, consequently, in place of one neutron entering a nucleus of uranium-235, the next fission will be caused by npk neutrons as a result of the processes of fission and moderation of the neutrons formed during fission. If $npk>1$, the number of neutrons initiating fission will increase after each act of fission. For this reason, the product npk is called the neutron "multiplication factor." For a chain reaction to take place it is necessary that the neutrons produced in the fission of one uranium nucleus should be able in their turn to initiate at least one fission of a new nucleus of uranium. Therefore, if the multiplication factor npk is greater than unity, the chain reaction will develop, but if the multiplication factor is less than unity, no chain reaction will take place.

Thus, three magnitudes (n, p and k), whose product must be greater than unity, decide the fate of the chain reaction.

* As we pointed out above, fission occurs in only 85 per cent of the cases of neutron capture by uranium-235.

Can we influence the values of these magnitudes? We can, but not of all of them. For instance, n, the number of neutrons produced in the fission of a single nucleus of uranium-235, is independent of our efforts. This is a very definite number and we have no way of altering it. But we can influence the number k, which denotes the fraction of slow neutrons initiating fission of uranium-235 nuclei. The remaining slow neutrons are captured by impurities in the uranium, by impurities in the moderator, by the nuclei of the moderator itself, and by uranium-238 nuclei. To increase the number k, it is necessary to increase the portion of neutrons captured by uranium-235 nuclei. To do this, it is first of all necessary to remove all impurities, especially cadmium, boron, and the like, which strongly absorb thermal neutrons. The next step is to select as neutron moderator such a substance as does not itself absorb neutrons at all or absorbs them to a very small extent. The best moderator of neutrons (hydrogen) is from this standpoint not exactly suitable, for it absorbs slow neutrons appreciably. Investigations of different substances have shown that heavy hydrogen (deuterium), graphite and beryllium are suitable moderators for a chain reaction. Of these three substances, graphite is most easily obtainable in sufficient quantities and of sufficient purity.

It is also possible to influence the number p. Given sufficiently pure uranium and moderator, neutrons may be lost during moderation only through absorption by the nuclei of uranium-238 and by escape through the vessel containing the uranium and the moderator. Absorption of neutrons by uranium-238 nuclei may be reduced in the following way.

A study of the absorption of neutrons of different speeds by uranium-238 showed that neutrons of different energy are absorbed differently. Uranium-238 nuclei are especially "eager" to capture neutrons of small energy, in the neighbourhood of five electron-volts (the so-called resonance absorption). Neutrons of energy above a thousand electron-volts and below five electron-volts are insignificantly absorbed by nuclei of uranium-238. If we want to keep neutron absorption by uranium-238 to a low level, we must see that when the neutrons lose energy they should

pass through this danger zone between 1,000 to five 5 electron-volts as rapidly as possible without encountering any uranium-238 nuclei.

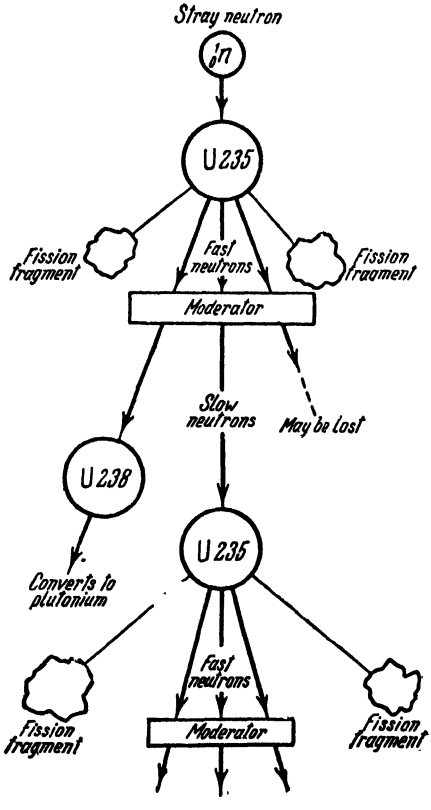


Fig. 55. Diagram of a chain reaction with a moderator in unseparated uranium.

To do this, the uranium is not distributed uniformly with the moderator throughout the volume of the pile, but is placed in the form of individual blocks separated by a moderator. Given such an arrangement, the bulk of the fast neutrons produced in fission will be slowed down to energies less than five electron-volts at a distance from the ura-

nium. These neutrons will pass through the danger zone of energy to the uranium and will be absorbed by uranium-235 nuclei, which will then undergo fission. Thus, the most advantageous arrangement is not the mixing of moderator and uranium, but a distribution in the form of a lattice in which the uranium and moderator alternate.

A further increase in p may be achieved by counteracting neutron loss from the vessel containing the uranium and moderator. Escape of neutrons may be reduced in two ways.

1. The size of the vessel should be made very large. The more uranium there is, the fewer neutrons will escape, which will result in a larger p and a bigger multiplication factor npk.

2. The vessel containing the uranium should be surrounded by a substance that reflects neutrons. Then a part of the neutrons will be reflected back from the reflector into the vessel with the uranium.

With sufficient quantities of pure enough uranium and moderator (figured in tons) it is possible to achieve such values of p and k that the multiplication factor will exceed unity, which will result in a chain reaction.

Fig. 55 is a diagrammatic sketch of a chain reaction with a moderator.

The Nuclear Reactor

An assembly in which a chain reaction may be realized is called a nuclear reactor or pile.

A uranium reactor is an enormous container filled with uranium and a moderator and surrounded by a substance that reflects neutrons. Let us take a general view of what happens inside a uranium reactor.

An essential point is the size of the reactor. Obviously, if the quantity of uranium in the reactor is insufficient (that is, if the uranium occupies a small volume), a chain reaction will not develop because too many neutrons will escape from the reactor. An increase in the volume of the reactor will reduce the ratio of the surface of the uranium to its volume (the surface grows in direct proportion to the square of the radius, while the volume increases as the

cube of the radius), therefore the fraction of escaping neutrons will diminish. At a certain size, called the *critical* size, a chain reaction is possible and the reactor begins to operate.

Now let us suppose that we have a reactor of such size that enables a chain reaction to develop. The number of nuclei undergoing fission per second will constantly increase. Since, as we know, approximately 200 million electron-volts of energy is released per fission per nucleus, the amount of energy produced will increase with the number of dividing nuclei. When the latter attain a sufficiently large figure, the energy release will reach a tremendous value. This process is illustrated in Table XI.

Table XI

Number of nuclei undergoing fission per second	10^{16}	10^{17}	10^{18}	10^{19}
Energy released in kilowatts (in round figures)	300	3,000	30,000	300,000

In principle, such a powerful energy release is entirely feasible. But in practice it is an extremely complex matter that requires the solution of a number of big and small problems.

1. A developing chain reaction results in a constant increase in the number of dividing nuclei. If we wish to maintain a constant number of fissions in time, we must learn to control the course of the reaction, that is, to regulate the number of fissions as required.

The solution of the problem is this: since the growth in the number of nuclear fissions is conditioned by the increase in the number of neutrons, regulation demands that we introduce into the reactor at a definite instant an additional neutron absorber. Since uranium-235 undergoes fission chiefly by thermal neutrons, neutron absorption may be controlled if we select a substance that effectively absorbs thermal neutrons. The most suitable materials were found to be cadmium and boron.

When these substances are inserted into a reactor, the conditions for the development of a chain reaction are

noticeably upset; if sufficient quantities of these substances are taken the reaction may be slowed down or even stopped altogether. This will obviously happen when the cadmium or boron introduced into the reactor reduce the factor k to such an extent that the multiplication factor npk falls below unity.

The diagram of a reactor given in Fig. 56 illustrates the principle of control. Here A is a volume containing

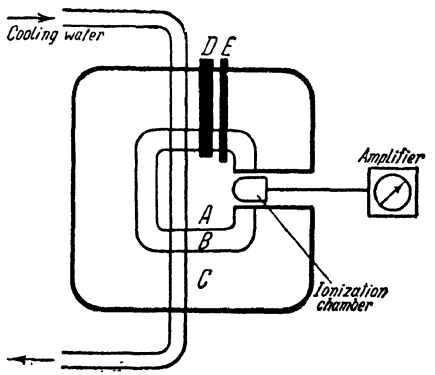


Fig. 56. Diagram of a nuclear reactor.

the uranium and moderator, B is the reflector of thermal neutrons. This reflector, which returns a part of the neutrons to the reactor, makes it possible to reduce the critical size. C is a shield that acts as a protection against the action of radiation of neutrons and gamma rays emerging in large numbers from the core of the reactor.

Reactor control is accomplished by means of rods D and E (made of cadmium or boron). Rod E (this may also be a group of rods) is able to move inside the pile. This rod is moved automatically by means of an ionization chamber connected with an amplifier. When the chain reaction has developed to the desired degree, radiation produced inside the reactor excites a definite ionization current in the chamber. If the chain reaction develops beyond the desired level, the ionization current in the chamber will rise above

the permissible value. An automatic device is then actuated and inserts rod *E* into the reactor. The movement of this rod will continue until the radiation inside the reactor, and hence the degree to which the chain reaction has developed, reach the required magnitude.

The purpose of the massive cadmium rod *D* is to stop the reactor. To do this, rod *D* is inserted. The large quantity of cadmium introduced into the reactor produces a marked reduction in the multiplication of neutrons, and the chain reaction is relatively quickly quenched.

2. In nuclear fission there arise fragments. All fragments are radioactive, emitting beta and gamma rays. Note also that neutrons are emitted in each fission process. A uranium reactor is thus a source of diverse radiations. Among these radiations, of special importance are neutrons and gamma rays because they possess considerable penetrating power. The intensity of this radiation is tremendous. By way of illustration let us take a medium reactor of 10,000 kilowatts. A reactor of this type produces in one second about 10^{18} gamma quanta and neutrons. This is immeasurably more than ever before obtained. Since gamma rays and neutrons exert exceedingly strong effects on the human organism, it is necessary to build a thick shielding arrangement as protection against these radiations.

The First Soviet Uranium Reactor

The fuel for the first Soviet reactor was natural uranium which consists chiefly of uranium-238. Natural uranium contains only a small amount (about 0.7 per cent) of the isotope uranium-235, the nuclei of which are fissionable by thermal neutrons. Due to the large number of uranium-238 nuclei, neutrons are captured by the nuclei of the combustible mixture (uranium-235 and uranium-238) essentially without subsequent fission, and the reproducibility of the neutrons is low. Accurate measurements carried out by P. E. Spivak and B. G. Erozolimsky show that on an average only 1.337 neutrons are produced per thermal neutron captured by uranium nuclei, that is, only 0.337 neutron remains for the development of the chain reaction.

This extremely small surplus of neutrons obtained when using natural uranium as fuel makes the problem of building a reactor exceedingly difficult. It was enough to lose during the slowing-down process a quarter of the neutrons produced and a chain reaction would not develop. This called for cutting neutron loss to a minimum; it was also necessary to make p and k approach unity so that the condition $npk=1$ could be satisfied even when $n=1.337$.

As has already been pointed out, in order to increase p (reduce neutron losses during moderation) it is necessary to use not a homogeneous mixture of uranium and moderator, but a lattice structure with the uranium and moderator alternating. The moderator used was graphite, since it is easily purified from all impurities that readily capture neutrons. The reactor was built up of graphite bricks ($100\times100\times600$ mm. in size) in which were drilled holes spaced 200 mm. apart. These were filled with 30- to 40-mm. diameter rods of metallic uranium.

To prevent the escape of neutrons it was necessary to take a large quantity of uranium and graphite. The first reactor began operation with a load of 45 tons of uranium, and several hundred tons of moderator. An added measure to reduce escape of neutrons was to arrange the lattice of uranium and graphite so that the surface around the reactor core was made as close to the form of a sphere as possible. This spherical surface had a radius of about three metres. The reactor had a reflecting layer of graphite 80 cm. in thickness. To house the reactor, a special building was put up. Its cross-section is shown in Fig. 57.

The nuclear reactor was assembled gradually, layer by layer. After each layer was put down, a measurement was made of the number of neutrons produced. These measurements were made with special care when the reactor approached its critical size. The reactor was adjusted and put into operation by means of cadmium rods.

The plan of the first reactor did not provide for constant removal of energy released during fission and so the reactor could not operate for a long time at a power level greater than about 10 watts. However, due to the large thermal capacity of the system the power level could be raised to a few kilowatts for short periods of time.

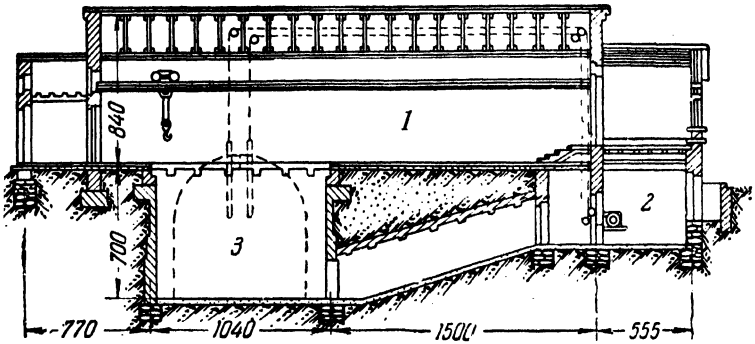


Fig. 57. Cross-section of building that housed the first Soviet reactor.
1 – main hall; *2* — laboratory; *3* — reactor; dimensions are in centimetres.

Experiments showed that a reactor of this type possesses the property of self-adjustment and is absolutely safe as far as possibility of an explosion is concerned. When the cadmium rod is removed, the power level of the reactor first rises to nearly 4,000 kilowatts and then several minutes later falls. This fall in power is due to a decrease in the multiplication factor when the reactor heats up.

The Atomic Bomb

Like the atomic reactor, the atomic bomb utilizes the energy released in the fission of nuclei of uranium or plutonium. In both cases, energy is released via the chain reaction. But whereas in the reactor an attempt is made to slow up the propagation of the chain reaction, in the atomic bomb the process of energy release occurs with exceeding rapidity. In atomic reactors the chain reaction is developed and maintained chiefly by slow neutrons. In the atomic bomb this is not possible, for the process of neutron moderation requires a certain lapse of time, which slows down the propagation of the chain reaction. This is why in atomic bombs the chain reaction is produced by fast neutrons, and no moderator is required.

But we know that fast neutrons do not produce a chain reaction in natural uranium, because there are too few atoms of uranium-235. If uranium consisted only of the isotope-235 or if its content in the mixture were substantially greater, a chain reaction could propagate rather rapidly without a moderator.

Here the thickness of the neutron reflector cannot be great so as not to increase the size and weight of the bomb. The absence of a moderator and the thinness of the reflector reduce the values of the factors p and k, and therefore to maintain a chain reaction (the condition is $npk \geqslant 1$) it is necessary to have high n, that is, a high content of uranium-235. Thus arose the problem of the large-scale separation of uranium isotopes.

Besides the separation of uranium isotopes, another possible way of accomplishing a chain reaction with fast neutrons was suggested, that of using plutonium-239. The fission properties of plutonium-239 resemble those of uranium-235. Plutonium is constantly being formed in uranium reactors. To obtain large quantities of plutonium one must build high-power uranium reactors. For example, to obtain one kilogram of plutonium in a 24-hour work-day requires a reactor of 1,500,000 kilowatts.

The building of high-power reactors was not the only problem that stood in the way of obtaining sufficient quantities of plutonium. The chemistry of this hitherto unknown element of plutonium had to be worked out. Without a knowledge of the chemistry of plutonium it would be impossible to extract plutonium from the uranium blocks of the reactor.

To get a clear picture of the difficulties of this problem, keep in mind that it was necessary to separate plutonium from uranium, which is chemically very similar to the former, in conditions where only minute quantities of plutonium are contained in huge amounts of uranium. The chemistry of plutonium was worked out, to the extent that satisfied the solution of this problem, by means of plutonium preparations obtained in cyclotrons. The amazing thing is that the required knowledge of plutonium chemistry was gleaned from a mere 0.5 milligram of plutonium.

Summing up, then, we find that either uranium-235 or plutonium-239 may be used as material for an atomic bomb.

Naturally, an atomic exlposion will be produced only if the chain reaction propagates rapidly. This implies that we must have plutonium or uranium-235 in the form of a solid piece that exceeds the critical mass (the critical mass, it will be recalled, is a quantity of fissionable material that fulfils the condition $npk=1$).

The atomic bomb consists of two or several pieces of uranium (or plutonium), the sizes of which are less than critical, and a device for bringing these pieces together into a

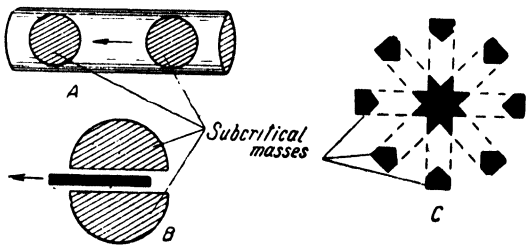


Fig. 58. Different ways of bringing subcritical masses together rapidly to obtain a critical mass.

solid mass. A chain reaction does not develop in the individual pieces, which are absolutely safe. However, when we bring them together we obtain a mass that exceeds the critical value, and a rapidly propagating chain reaction will be initiated leading to a powerful explosion.

The separate pieces of uranium must be brought together with extreme rapidity. If this is done slowly they will fall to pieces due to thermal overheating and the bomb will disintegrate without exploding. When the pieces of uranium or plutonium are brought together rapidly, a chain reaction will have time to develop before the explosion destroys the bomb shell. Strictly speaking, the atomic bomb is a device for the rapid joining of parts of uranium (or plutonium).

Fig. 58 gives a diagrammatic sketch of several possible ways of joining subcritical masses of nuclear explosives. In Fig. 58,*A* are two subcritical masses with sufficient separation that are brought together by the action of a trigger mechanism. The high-speed trigger mechanism is an explosion of a small amount of an ordinary explosive.

Figuratively speaking, to produce an atomic explosion one must shoot one piece of uranium at another.

Fig. 58, *B* shows that two subcritical masses separated by a spacer may be brought together by removing the spacer. Fig. 58,*C* shows an arrangement of subcritical masses surrounding a single subcritical central piece. A trigger mechanism sends the peripheral masses rushing into the centre. The result is an atomic explosion.

The action of an atomic explosion depends on the conditions in which it is produced, whether high above the earth, at the surface of the earth, under water and so forth. The first stage of an explosion in air shows the characteristic ball of fire (see Fig. XLI, in the Appendix). The reaction products are under a very great pressure. The temperature in the zone of the reaction exceeds a million degrees. The air about the bomb heats up to incandescence, and the light flash is seen at a distance of over 100 km.

The ball of fire grows rapidly reaching 500 metres in diameter. As it expands it moves upwards like a balloon at a speed of several tens of metres per second. At a height of 12 to 15 km. where the density of the surrounding air is roughly equal to the density of the ball it takes on the shape of a mushroom, forming a flat cloud with a radius of several kilometres, which lasts until it is dispersed by the wind.

Simultaneously with the formation of the ball of fire, in the centre of the explosion there appears a shock wave. This wave propagates from the centre through the ball of fire at a speed exceeding that of sound.

The atomic bomb is a source of diverse radiations. Large quantities of neutrons and gamma rays, and also visible, infrared and ultraviolet radiations are emitted at the instant of explosion. The neutrons and gamma rays are produced in the process of fission; while light radiation is due to heating. After the explosion, the affected site exhibits gamma and beta rays originating from beta decay of the fragments, and also alpha particles from unsplit uranium nuclei.

In an underwater explosion, an enormous gas bubble is observed in place of the ball of fire. The bubble develops from the rapid evaporation of water and bursts at the water

surface at the same time that the shock wave arises. In the act, an enormous volume of water rises up forming a dome-shaped cloud (see Fig. XLII in the Appendix). A wave reaching 30 metres in height appears on the water surface. This wave represents a serious hazard to ships and structures on the shore.

As it bursts at the water surface, the gas bubble produces an instantaneous huge spray dome. The inrushing water produces a column of spray called a "plume" (see Fig. XLIII in the Appendix). The plume is in the form of a hollow cylinder with a maximum diameter of the order of 600 metres and walls about 90 metres thick. In this process, up to one million tons of water are thrown up into the air.

The plume rises to a height of 1,800 to 2,400 metres where it encounters the colder layers of air; its upper part is in the form of a cloud resembling a cauliflower. As the rise of the plume slows down, the lower part begins to fall back into the sea, and at the base of the plume there develops a gigantic wave 250 to 300 metres in height that consists of a cloud of mist. This wave is known as the base surge. The base surge travels outwards from the site of the explosion and gradually lifts above the surface of the sea merging with low cumulus clouds over the site of the explosion. If there is a wind, such clouds travel great distances. There begins a rain of radioactive water.

If the bomb is detonated at the surface of the earth a crater is formed and a large quantity of ground is thrown up into the atmosphere. The atoms of radioactive isotopes adhere to dirt particles and fall back to earth; this is known as fall-out. The result is that in the area of the explosion there is a considerable local concentration of radioactive substances. The shock wave and thermal action of an earth-surface explosion are also very intensive, but they affect a smaller area than in the case of an air explosion.

The explosion of an atomic bomb is capable of tremendous destruction. The shock wave creates big pressures even at relatively large distances from the site of the explosion. It is capable of inflicting serious damage on massive city buildings within a radius of about a kilometre from the point of explosion.

Thermal radiation likewise represents a considerable haz-

ard. Approximately one-third of the total energy released in the explosion of an atomic bomb passes into radiation, producing something like 5×10^{12} calories. Thermal rays propagate at the speed of light (300,000 kilometres per second) and set fire to combustible materials.

Likewise very dangerous are the radioactive radiations that arise in the explosion area. It should be pointed out that the action of gamma rays and neutrons are a real hazard over roughly the same area that is affected by the action of the shock wave and thermal rays. An added hazard are the beta-radioactive substances that remain after the explosion. Their radius of action depends on the nature of the explosion and the direction of the wind.

At the present time numerous measures for protection against atomic attacks have been developed and tested. Among the most reliable forms of protection are various subterranean arrangements and special shelters to provide reliable protection for people from the after-effects of an atomic explosion.

Chapter XIII

THE PEACEFUL USES OF ATOMIC ENERGY

Atomic Power Stations

The first electric station to work on nuclear fuel was built in the Soviet Union by a team of scientists, engineers and technicians under the leadership of Blokhintsev and Krasin and began operation on June 27, 1954, with a useful power output of 5,000 kilowatts.

The design of the atomic power station embodied the following principles. Due to fission of uranium nuclei in the atomic reactor during operation a large quantity of energy is liberated. The energy released is carried off by fragments, neutrons, electrons and gamma quanta, during the deceleration of which it is converted into heat which raises the temperature of the core of the reactor. This heat may be used to evaporate water or other suitable liquid and to create sufficiently high-pressure vapour. The vapour obtained can drive a turbine together with a connected generator of electric current. The turbine and generator can be exactly like those used in conventional thermal power stations.

The building of an atomic power station required the solution of a series of new problems.

The electric station should naturally be made to operate continuously for a long period of time. During this long time the initial supply of nuclear fuel gradually "burns up" due to fission. On the other hand, there accumulates in the reactor a large quantity of fission products, fragments (radioactive slag) that absorb thermal neutrons. Among them are the poisoning xenon-135 nuclei that "avidly" capture thermal neutrons. Owing to the fission of nuclei of uranium-235 its concentration in the combustible mixture dimin-

ishes, while the concentration of xenon-135 increases. Together these factors reduce k and the product npk progressively decreases during operation of the reactor. To keep the product npk equal to unity despite the accumulation of slag in the reactor and the diminishing quantity of uranium-235, it is necessary beforehand to provide a surplus supply of fuel in the reactor and to have a method of regulating the power output. To do this, one must insert into the active core of the reactor substances that intensely absorb thermal neutrons. In the reactor of the atomic power station, rods of boron carbide are used for this purpose. There are in all 18 such rods: six are arranged near the centre of the core and 12 on its perimeter. As slag accumulates and the quantity of uranium-235 diminishes in the combustible mixture, these rods are withdrawn from the pile. The result is a reduced loss of thermal neutrons, that is, k increases and conditions are maintained that are necessary for the development of the chain reaction ($npk \geqslant 1$).

A reactor cannot operate with natural uranium, since from the very beginning large quantities of neutron-absorbing substances have to be introduced into the reactor. For this reason, the fuel selected was a uranium mixture enriched with the isotope uranium-235.

The reactor of the first atomic power station was loaded with uranium which contained five per cent of the isotope uranium-235 (in place of the 0.7 per cent in natural uranium). This concentration of uranium-235 permits operation of the reactor to be started with the total of 18 boron carbide rods inserted. Enrichment of the uranium also permits of reducing slightly the size of the reactor and the radius of the core. The reactor core (fuel and moderator) of this station has the shape of a cylinder 150 cm. high and 170 cm. in diameter. In Fig. 59, which is a cross-section of the reactor, the core is shown by a dashed line. As in the first Soviet reactor, the moderator was graphite with uranium rods arranged in the form of a regular spacial lattice. One hundred twenty-eight special slots were made for placement of the rods in the graphite.

The reactor of an atomic power station should generate heat, which produces steam that drives a turbine. The heat is liberated chiefly in the uranium slugs. Under normal

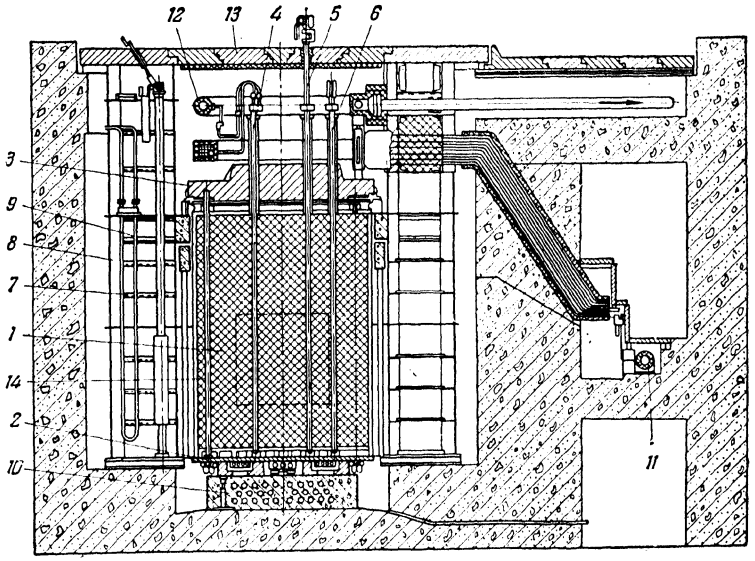


Fig. 59. Reactor of atomic power station.

1 — reactor assembly; *2* — bottom plate; *3* — top plate; *4* — operating channel; *5* — emergency channel; *6* — automatic control channel; *7* — ionization-chamber channel; *8* — side shielding (water); *9* and *10* — refrigerators; *11* — distribution main; *12* — collecting main; *13* — top shielding (iron); *14* — cooled support of reflector.

conditions the flow of heat released from the surface of the uranium amounts to a million and a half large calories per hour per square metre. To remove this heat, the uranium slugs must be intensively cooled. In the power station reactor, cooling is accomplished by using ordinary water under high pressure. Since uranium is strongly corroded by water, each uranium rod must be jacketed in a thin-walled tube of stainless steel, and all this together must be placed in another such tube so that the cooling water should move in the space between the two concentric steel tubes.

With a fresh load of fuel the reactor can operate for two and a half months, after which the uranium rods must be replaced by new ones (by this time the content of uranium -235 in the rods is equal to 4.2 per cent).

Just as in the first Soviet reactor, graphite was used as the material for the neutron reflector. The active core was

located inside a graphite masonry with walls 80 cm. thick. The entire masonry was enclosed in a hermetic steel casing filled with helium and resting on a concrete foundation. The reflector housed the boron carbide rods designed to maintain a given power level of the reactor. As the power level rises the rods are automatically inserted into the reactor, and as it falls they are removed slightly. Besides the automatic control rods and rods for compensating uranium burn-up and the formation of slag, there were two safety rods for rapid stopping of the reactor. At an emergency signal these rods fall into the active core of the reactor. Neutron absorption gives a sharp rise, the neutron multiplication factor falls below unity and the chain reaction ceases.

The reactor of an atomic power station has special channels for neutron irradiation of different substances. The density of the neutron flux in these channels reaches 8×10^{13} *neutrons/cm*$^2 \times$ *sec.*

The biological shield of the reactor is a layer of water one metre thick and a concrete wall of three metres in thickness. In the upper part of the reactor, the biological shield is in the form of an extra thick graphite reflector, and also a steel cover and an iron plate.

As we have already pointed out, heat is removed from the reactor by continuously circulating water. The water that cools the reactor circulates in a hermetically sealed circuit and passes through a special heat exchanger. In the heat exchanger, heat from the water circulating in the first circuit is conveyed to the water circulating in the second circuit, converting the latter into steam, which drives the turbine and electric generator. A diagrammatic sketch of an atomic power station is given in Fig. 60.

Every phase in the work of an atomic station is automatically controlled by means of high-speed instruments and through circuits from a central control panel.

The operation experience of the first atomic power station has given much information for assessing the economic indices of such stations. The cost of one kilowatt-hour of electric power produced at the first atomic station has proved higher than the average cost of a kilowatt-hour at conventional thermal electric stations. However, there are

already many ways of reducing the cost of atomic-produced electric power.

The economic indices of a recently designed 100,000-kilowatt atomic station are found to be close to those of thermal power stations of the same power. Although the cost of nuclear fuel (as calculated per kilowatt-hour) slightly exceeds that of the fuel of a coal-burning station, a number of favourable points, such as lower power consumption for the requirements of the station itself, the absence of large fuel storehouses. of a system of fuel delivery, of coal

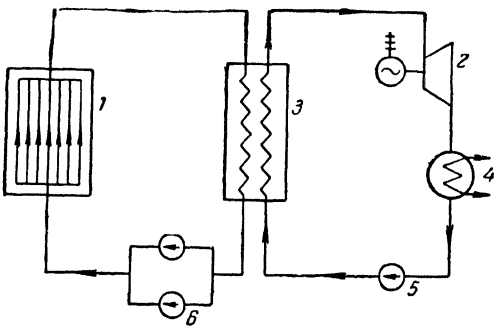


Fig. 60. Schematic diagram of atomic power station.
1 — reactor; *2* — turbogenerator; *3* — heat-exchanger; *4* — condenser; *5* and *6* — pumps.

grinding mills, and other large-size structures that are necessary components of all coal-fired stations, make atomic power stations a fully profitable source of energy. A nuclear station may be more economical than a coal-fired station at remote distances from where the coal is mined or operating on low-grade fuel. The future development and refinement of atomic power stations will make them still more economical.

In order to get a better concept of the possibilities of development of nuclear power systems for peaceful purposes, one must not overlook the fact that a nuclear reactor not only generates heat, but also, simultaneously, fresh nuclear fuel. The bulk of natural uranium consists of the isotope

uranium-238, which is not fissionable by slow neutrons. As was pointed out earlier, the penetration of a slow neutron into the nucleus of a uranium-238 atom does not fission the nucleus, but leads to the formation (by two beta transformations) of the isotope plutonium-239. Plutonium-239 is also a nuclear fuel that suffers fission by slow neutrons. This is why a nuclear reactor not only consumes nuclear fuel (uranium-235) but also creates it (plutonium-239).

In the reactor of the first Soviet nuclear power station, the breeding ratio of plutonium is relatively small, 0.32 (which means that 32 atoms of plutonium-239 are produced per 100 consumed atoms of uranium-235). But it may be increased. In fast-neutron reactors the breeding ratio of plutonium is substantially greater, having a theoretical value of 1.5. If the breeding ratio of plutonium is unity, a reactor during operation will consume and produce the same amount of fuel. Now if this ratio is greater than unity, the quantity of freshly produced fuel will exceed consumption and the reactor will be a source of additional nuclear fuel.

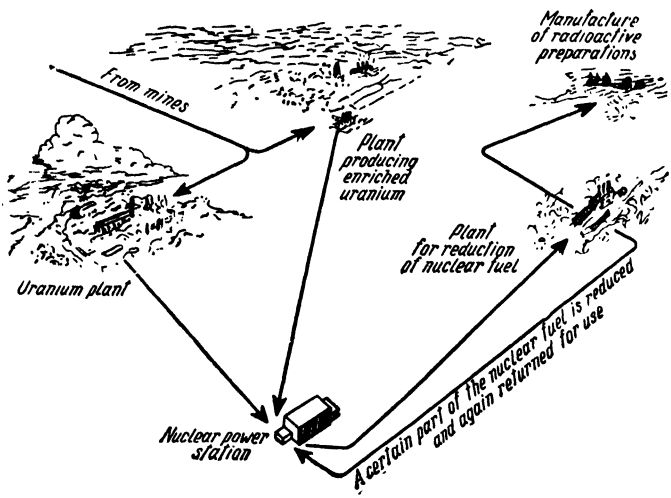


Fig. 61. A combination type atomic-power system.

A further peculiarity of a nuclear reactor is that it produces not only energy and nuclear fuel, but also radioactive isotopes. These isotopes are periodically removed from the reactor and made use of in the economy. This shows that nuclear power systems should be developed as combination units.

Fig. 61 shows the plants and establishments involved in such an integrated operation of a nuclear power station. The composite utilization of nuclear reactors and refinement in their design will undoubtedly improve their economical aspects.

The Soviet Union has extensive plans for the construction of new atomic power stations. During the period 1956-60, nuclear stations will be built with an aggregate power output of 2 to 2.5 million kilowatts. They will be located primarily in areas that have no fuel supply of their own. Nuclear power stations are also being built in England, the U.S.A., Canada and France.

Atomic Power Plants

The great advantage of nuclear reactors is that the production of energy involves only a tiny consumption of fuel. For example, 8.2×10^{10} joules are evolved in the fission of one gram of uranium-235. Even if we take into consideration the fact that when heat energy is transformed into work only 25 per cent of this energy is usefully used, the fission of one gram of uranium will be enough to run a 100,000-kilowatt engine for 3.5 minutes. Only 12 kilograms of uranium-235 would be required to keep such an engine running for a whole month.

Fig. 62 is a graphical illustration of the quantities of different types of fuel that can suppy the same amount of energy.

A further essential advantage of nuclear fuel is that its "burn-up" does not require any additional materials, such as oxygen, for instance, whereas the burning of one ton of carbon requires 2.66 tons of oxygen. The harnessing of atomic energy will enable powerful engines to be built, which

will be capable of working for long periods of time without refuelling or taking on supplies of other materials.

But one has to keep in mind that the use of atomic power plants involves the resolution of many difficult problems. The nuclear reactor, which is the principal part of the plant, is ordinarily very large in size and weight. An atomic engine is peculiar in one respect. It cannot be started before it has been completely filled with fuel, and the "capacity" of its "tank" is tremendous. True, the critical size of the reactor may be reduced if the fuel is highly enriched uranium and the moderator is water (either ordinary or heavy) in place of graphite. In water the neutrons are slowed down more quickly than in graphite, thus considerably reducing the critical size of the reactor. The over-all volume of the reactor may also be reduced by making the reflector thinner when graphite is replaced by substances that contain hydrogen. All these factors are capable of reducing the volume and weight of the reactor appreciably. In a reactor with enriched nuclear fuel dissolved in water, the core may be very small, of the order of 30 cm. in diameter, while the thickness of the shield will not exceed two metres. A chain reaction will begin with a fuel load of approximately one kilogram.

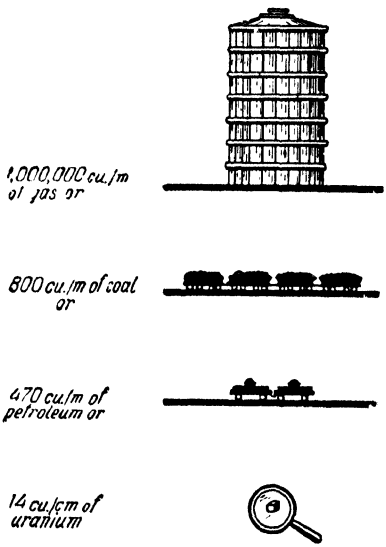


Fig. 62. Volumes of atomic and other fuels that produce the same amount of heat.

A cut in the weight and volume of nuclear reactors makes them suitable as a source of power for engines; however, it is clear that the construction of "portable" engines, such, for example, as may be installed in an automobile, is not yet feasible practically.

Nuclear reactors may be used in the construction of very powerful plants designed for operation over very long periods of time.

An atom-powered submarine called the *Nautilus* with a displacement of 2,700 tons has been built in the U.S.A. It is fuelled with uranium enriched with the isotope-235. The heat generated by uranium fission is removed by ordinary water which at the same time serves as moderator. The water circulates between the reactor and the boiler heat-exchanger unit, where it transfers its heat to the water of the secondary circuit. The turbine develops 8,000 h. p. and drives an electric generator which feeds the engines that turn the propellers of the *Nautilus*.

The design speed of the *Nautilus* is 37 km./hr. under water and 65 on the surface. It is expected to be capable of a round-the-world voyage without refuelling.

A second American submarine, the *Sea Wolf* has recently been completed.

In the Soviet Union, the attention of scientists is centred on problems connected with the peaceful application of atomic energy. The directives of the Twentieth Congress of the Communist Party of the Soviet Union on the Sixth Five-Year Plan envisage utilization of atomic energy in ships, on railway transport and in aircraft. One of the tasks is to build an atom-powered ice-breaker capable of making long voyages in the Arctic ice without having to stop at any port. This ship has been built now.

The Soviet atom ice-breaker, the first in the world, is expected to have a displacement of 16,000 tons. Its main engines will develop 44,000 h. p. The ship will be able to take on board sufficient supplies to last for a year's voyaging without putting in to port. The hull of the atom ice-breaker will be much stronger and heavier than that of ordinary ice-breakers, thus making it possible to sail in thicker ice fields.

Tracer Atoms and Their Use in the National Economy

The discovery of artificial radioactivity placed in the hands of scientists a remarkable tool for research: "tracer atoms." What are these tracer atoms and how are they used?

We already know that radioactive substances are unstable. They decay and in time "disappear." The disintegration of each radioactive substance is accompanied by the emission of alpha, beta and gamma rays. Radioactive radiation may easily be registered (for example, by means of a Geiger-Müller counter), thus making it possible to detect the atoms of the radioactive isotope among other substances, including the atoms of the nonradioactive isotopes of the given element. The character of the radioactive radiation (the nature of the particles, the magnitude of their energy, their half-lives) always gives the clue to what radioactive isotopes are present in the given substance. If we are able to locate radioactive atoms, we are able to follow the behaviour of the substance that interests us.

By way of illustration, let us assume that a mixture of different substances contains phosphorus. We then add to this mixture a small amount of radioactive phosphorus that is sufficient for it to be registered by its radiation. If we subject our mixture to chemical action, chemical reactions will take place, with some of the substances going into solution, others into the solid state, and yet others into the gaseous state. What will happen in these processes to the phosphorus? In what state will it be after the reaction?

The answers to these questions are given by determining the location of the radioactive radiation either in the liquid, gas or solid part. Phosphorus will be found where radioactivity is detected. Since, chemically speaking, both the radioactive and nonradioactive isotopes are absolutely identical, there will be no difference in the fate of the radioactive and nonradioactive phosphorus. Nonradioactive phosphorus will be found wherever the radioactive variety is. Thus, by observing the behaviour of a radioactive isotope we can determine the behaviour of the element that interests us.

Radioactivity is the tag which enables us to trace the actions of the atoms. Hence the name tagged atoms or tracer method.

Nuclear reactors make it possible to produce large quantities of different radioactive isotopes. Radioisotopes were obtained before the advent of nuclear reactors and even before the discovery of nuclear fission. For instance, they may be obtained in cyclotrons by irradiating various substances

in a beam of fast deuterons or alpha particles. But only very small quantities of radioactive isotopes can be had in this way, the cost being prohibitive.

The construction of nuclear reactors produced a crucial change. Stupendous numbers of neutrons are created in such reactors. A portion of them go to maintain the chain reaction, while the remainder may be used for the production of radioactive isotopes.

When a neutron enters a nucleus it alters the composition of the latter to produce an unstable radioactive nucleus. In a reactor, radioisotopes arise not only from neutron irradiation, they are also produced in the fission process of uranium nuclei. The fission fragments are radioactive too and they must be removed from the reactor because they interfere in its normal operation. But fragments are usually removed only when the reactor has been shut down, which is a thing not done very frequently. For this reason, the principal source of radioactive isotopes is neutron irradiation of different stable elements introduced into the reactor.

Of course, not all radioactive isotopes find application. Table VI (p. 220) gives a list of the more important radioactive isotopes. Many of the chemical elements are represented in this list. Of course, elements not listed also have radioactive isotopes, but in the majority of cases their half-life periods are small and so the isotopes are not suitable for widespread use.

Registration of tracer atoms is rather simple. Geiger-Müller counters and photographic procedures are the most common methods of registration. Photographic methods are usually resorted to when it is necessary to determine the distribution of tracer atoms in a given section of the body under investigation. They consist in holding a photographic plate to the area in question and then in developing the plate. The radioactive radiations light the plate, which on development exhibits dark spots. The distribution of the dark areas on the plate is an indication of the distribution of radioactive substance in the body being studied. Such pictures obtained by the action of radioactive radiation are known as "radioautographs."

For examples of radioautographs, see Figs. XLIV and XLV in the Appendix. Fig. XLIV is a radioautograph of

a tomato leaf fed with radioactive phosphorus. This picture is obtained by putting the leaf on a photographic plate wrapped in black paper. Fig. XLV shows radioautographs obtained from sections of a tomato fed with radioactive zinc. Both pictures clearly exhibit the areas of concentration of radioactive substances; they show what parts of the plant assimilate best the salts that included the radioactive substance as constituent.

Tagged (or tracer) atoms find broad application in science and technology. It is beyond the scope of this book to give detailed descriptions or even a list of all these applications. We shall select only a few as illustrative examples.

Tracer techniques are of great value in studying the processes that occur in living organisms. It is common for an organism, functioning normally, to ingest those chemical elements which already comprise a substantial part of the organism (oxygen, hydrogen, nitrogen, iron, sodium, etc.). Naturally, a chemical analysis, which, as it stands, is a big problem when dealing with living bodies, does not permit of differentiating between the atoms introduced into the organism and those originally there. Tagged atoms are something quite different. They may be easily detected even when the related chemical elements are already present in the organism.

It should also be noted that Geiger-Müller counters are extremely sensitive, being capable of recording every single radioactive act, that is, the decay of individual atoms. This makes investigation possible with such infinitesimal admixtures of the radioactive substance that their presence is absolutely harmless to the organism.

Frequently the observation technique is simplicity itself, as in the study of the rate of absorption of different salts by the stomach. In this case, the experimenter simply holds a Geiger-Müller counter in his hand after swallowing the salt in question together with an admixture of the proper radioactive substance. The salts absorbed into the stomach are carried by the blood stream to all parts of the body, including the hand with the counter. The time of the pulse in the Geiger-Müller counter is an indication of the rate of absorption of these salts.

Tracer atoms have shown themselves to be invaluable in the search for new medicines. As an example, take an illness like hypertension, which has to do with high blood pressure. This illness is treated by substances that help to dilate the blood vessels. In dilated vessels the blood flows under a smaller pressure. To determine the vessel-dilating action of different substances a person is given radioactive sodium (injected into a vein of the hand) or radioactive xenon (via the respiratory system) together with the substance under study. Geiger-Müller counters are used to observe the appearance of activity in different parts of the body. In a healthy person, it takes 40 seconds for the blood to get from the wrist of the hand to the feet. If medicine is taken that dilates the blood vessels, this time is cut to from 20 to 30 seconds.

The use of tracer atoms has made it possible to determine the rate at which different substances move to the various parts of the body, to find the rate of their metabolism and to find out in what part of the body a given substance accumulates. It was found, for example, that on entering the organism iodine concentrates chiefly in the thyroid gland. This made it possible to use radioactive iodine to fight certain forms of disease of the thyroid gland.

Tagged atoms are invaluable to the surgeon. When operating tumours of the brain it is particularly important to know the exact site of the tumour. This is found out by using radioactive iodine. The iodine compound, diiodofluorescein, is selectively absorbed by the tissue of the tumour. This compound, tagged with radioactive iodine and injected into the organism, concentrates in the tumour and emits gamma rays that unerringly indicate the site of the tumour.

Tracer techniques are widely used in the study of highly complex biochemical processes that underlie the activities of the nervous system. A study of biochemical processes in the cortex during sleep has shown that the processes of synthesis predominate over the processes of disintegration; this leads to a restoration of the working capacity of the brain during sleep.

Tracer atoms are playing a big role in agriculture. They are being used to find effective ways of raising crop yields, for by studying how plants assimilate nutrients it is possible to work out optimum food rations. Thus, radioactive phos-

phorus helped to find the best way of placing fertilizer in the ground so as to ensure a sufficient supply of phosphorus to the roots of young plants. Experiments have shown that the most rational method of applying phosphates (at least granulated superphosphate) is during planting and by placing it directly in the rows. This method ensures optimum nutrition for the shoots even when small doses are applied.

Tracer atoms permit of finding the best periods for fertilizing plants. It was found, for instance, that maize assimilates phosphate fertilizers during the early period of vegetation. At the later stages its deeply germinating roots extract straight from the unfertilized soil the bulk of the phosphorus that it needs. In contrast to maize, potatoes get a constant supply of phosphorus from fertilizers. Experiments performed with tobacco have shown that phosphate fertilizers used in tobacco planting are not very effective.

Radioactive carbon has helped scientists to establish that the root system plays a far more important role than that of transferring to the plant substances extracted from the soil. The root system itself transforms mineral substances into organic substances. In contrast to the accepted view, the roots of plants also extract from the soil carbon dioxide and its salts and convey it to the leaves where it is assimilated. It was in this way that a new additional source of carbon nutrition for plants was discovered and also a new function of the roots. This function had been thought earlier to be performed solely by the green parts of the plant.

It was also found that the leaves can take upon themselves the usual function of the roots in supplying the plant with minerals. This is now utilized in the so-called non-root fertilization of plants. The application of this new method of fertilization has raised cotton yields 10 to 15 per cent. At present non-root fertilization of cotton plants is widely employed in this country.

Substances move much faster in the plant than was earlier thought. To check the rate of movement of sugar in a plant, radioactive sugar (containing the radioactive isotope carbon-14) was introduced into the cells of a green leaf. The sugar was found to move through the plant at the rate of 70 to 80 cm. per hour. Water has a still higher rate of movement, up to 14 metres per hour. Substances moving from the roots

to the leaves cover two to four metres per hour. Plastic substances move from the leaves to the roots or to the fruit at a rate of 1 to 1.5 metres per hour.

Plants are somewhat like microscopic factories that utilize three principal forms of "raw material" — water, carbon dioxide and sunlight. The sun supplies the energy by means of which the water and carbon dioxide are synthesized to carbohydrates. The secret of how a green plant grows has engaged many generations of scientists. Tracer atoms have now put into the hands of research men a new method capable of probing this persistent secret of nature. Tracer methods pointed to the feasibility of carbon dioxide being assimilated and reduced outside the cell. It was also possible to establish the important role in this process of iron-containing compounds. It was shown that in the process of photosynthesis plants produce not only carbohydrates (as was earlier believed) but also proteins. It was possible to confirm the direct participation of water in the formation of oxygen evolved in photosynthesis and to identify the intermediate products of photosynthesis.

Labelled atoms help archaeologists to determine the age of ancient specimens. Here use is made of radioactive carbon-14 with its half-life period of 5,700 years.

It has been established that due to neutrons produced from the interaction of cosmic radiation and the earth's atmosphere, there takes place a partial transformation of nitrogen-14 into radioactive carbon-14.

$$_{7}N^{14} + _{0}n^{1} \longrightarrow _{6}C^{14} + _{1}H^{1}.$$

Insofar as cosmic-ray intensity is constant in time, the concentration of $_{6}C^{14}$ also remains unchanged. Radioactive carbon-14 is found wherever there is ordinary carbon. It participates in all processes in nature that involve carbon. Carbon metabolism occurs in every living organism. In assimilating carbon from the air, a plant receives carbon-14. For this reason, the cellulose of living plants should contain radioactive carbon, the concentration of which is relatively small, there being only about 50,000 million atoms of carbon-14 per gram of carbon in the cellulose of any plant. This makes it possible not only to establish reliably

the presence of carbon-14 in a plant, but also to determine the quantity.

While the plant lives the concentration of radioactive carbon in it remains constant. The disintegrating carbon is continuously being replaced by new carbon. When the plant dies carbon metabolism ceases and the plant stops receiving new radioactive carbon. The quantity of radioactive carbon in it begins to diminish. In 5,700 years it will have diminished by one half, in 11,400 years to $\frac{1}{4}$ of the normal quantity, and in 22,800 years there will be only six per cent. The archaeologist has only to find some wooden object in the excavations of an ancient settlement and to determine the quantity of radioactive carbon that it contains. Then by means of a simple calculation he is able to state how much time has elapsed since the plant died. This is enough for him to conclude when the ancient settlement existed.

Tracer atoms are capable of giving much valuable information in geological prospecting. Naturally, in the search for nuclear fuel (uranium and thorium) wide use is made of the radioactive properties of these elements. But tagged atoms can help in prospecting for petroleum, too.

In oil prospecting, wells are sunk in areas where oil may be expected to be found. The old method was to take rock samples during drilling of holes. By analysing these rocks, a determination was made of the nature of the structure and the order of the layers through which the drill hole passed. This simple method of geological exploration was in reality a very unwieldy and expensive one. To obtain only one rock sample it was necessary to raise and unscrew at times more than a kilometre of piping. Prospectors are naturally interested in other, simpler methods of prospecting.

One such method is the following. A Geiger-Müller counter is lowered into the well to register the radioactivity of the rocks through which the well passes. Different rocks have different radioactivity. Clayey rocks, shales and phosphorous limestones have a high radioactivity, while oil-bearing sands have a low activity. By correlating in adjacent wells the variation of radioactivity with depth, it is possible to study the occurrence of the oil layers.

In another method, use is made of the fact that neutrons are reflected in different ways from different types of rock. Due to reflection, a "neutron cloud" is formed near the neutron source and the size of the cloud depends on the surrounding rocks. Neutrons are easily absorbed by stable nuclei with the result that gamma-ray quanta are ejected. If the neutron cloud is small, the quanta will be generated near the source of the neutrons. But if the neutron cloud increases in size, the quantity of gamma quanta appearing near the neutron source will diminish, while at great distances from it there will be an increase. Let us place a Geiger-Müller counter at a distance of 60 to 80 cm. from the neutron source. When passing an oil-bearing layer, the neutron cloud diminishes in size markedly, and the counter shows a sharp decrease too.

An idea may be gained of the extent to which tracer atoms are used in oil prospecting in the U.S.S.R. by the fact that as early as 1954, these techniques were employed in exploring 3.5 million metres of wells. As a result of this exploration many of the old abandoned wells were brought back to life.

Registration of tracer atoms is an exceedingly sensitive process. An infinitesimal amount of radioactive substance is required for them to be detected. This peculiarity of radioactive substances has found a range of important applications.

In electrolytic processes, the used electrolyte is disposed into rivers. But this cannot be done directly, since the electrolyte contains harmful impurities, which must not be allowed to get into the river water. These harmful impurities are retained by a system of filters. An exceedingly important thing is to determine the instant of filter saturation, that is, when the filter loses its absorbing properties. This is done by adding to the electrolytic bath a suitable radioactive substance that "tags" the harmful impurity. This substance passes through the filter together with the electrolyte and is retained together with the impurities which must be filtered out. When the filter is saturated and ceases to retain the harmful impurities the radioactive material begins to pass through it, and this is easily registered by a counter placed behind the filter.

Tracer atoms may be used to trace the movement of noxious gases in shops, to determine the areas where gases are "stagnant," to solve problems connected with the selection of a rational arrangement of flues, ventilation plants, etc.

Tracer atoms are of use in the machine-building industry, too. Recall the age-old fight for longer lifetimes for machines, for durability of the harder-working machine parts, and the struggle against wear (selection of lubricants of proper quality, and of alloys that give minimum wear in mutual friction) which is one of the most important problems of the field. The solution of these problems by ordinary procedures is expensive and takes a very long time since wear tests cannot be done in a hurry. Here tracer techniques simplify the task immensely.

The rubbing surfaces are made radioactive either by neutron irradiation or by adding radioactive substances to the alloy out of which the parts under study are cast, or by pressing radioactive materials into them. During friction, minute particles of metal are torn away from the rubbing surfaces and get into the lubricant. By putting a Geiger-Müller counter in the tank or crankcase with the lubricant, it is possible to register the appearance in the lubricating oil of tiny traces of radioactivity and to get an idea of the extent of wear of the rubbing surfaces long before any visible signs of wear are apparent. The time required for a wear test is cut by tens of times. Besides, it is possible to test not individual parts or laboratory samples, but the working machines in ordinary production conditions. By putting "tags" of different radioactive substances on various parts of the machine, it is possible to get an idea of the degree of wear of the different parts.

In metallurgy, tracer atoms are used to control the steel smelting process. They permit of making an exceedingly rapid check of the chemical composition of the steel; it is also possible to determine the origin of harmful impurities in the metal. As an example, sulphur (a highly undesirable admixture in steel) may enter the metal both from the coke and from the charge itself. By adding sulphur-labelled coal to the load put into the furnace, it is possible to determine what part of the sulphur passes into the metal from the coal and charge as a result of smelting.

Tracer atoms help to grade steel. Anyone knows what a complicated and unpleasant job it is to establish the grade of a sample of steel if for some reason the tag has been lost. By adding various radioactive substances (in quantities that in no way affect the properties of the steel) to definite grades of steel, it is a simple matter to determine the grade of different pieces without resorting to a chemical analysis.

Tracer atoms help to follow the level of the charge in blast furnaces. If we place on one side of the furnace a gamma emitting radioactive material (for example, cobalt-60), and on the other side a Geiger-Müller counter (Fig. 63), the latter will respond readily to a sinking of the charge below the level AB because the charge absorbs a substantial part of the gamma rays that pass through it. A signal from the counter actuates an automatic device that regulates the loading system of the furnace, and the required level of charge will be immediately restored. Radioactive level gauges may be used in a large number of other production processes.

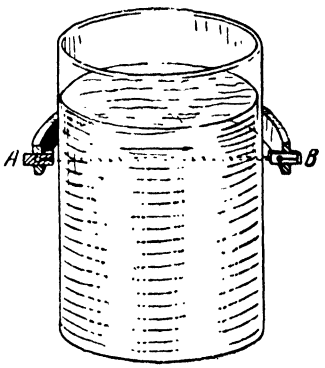


Fig. 63. Determining the charge level by means of a Geiger-Müller counter.
A — gamma-ray source;
B — counter.

Tracer atoms are a wonderful method of production control. The absorption of radioactive radiation depends not only on the properties of the radioactive radiation itself, but also on the properties of the absorbing medium, its composition, density and thickness. The dependence of absorption on thickness may be used in the control of rolled goods, especially in the rolling of foils. Since foils are very thin, the slightest variation in the degree of compression affects the foil thickness perceptibly. The small thickness of foil permits the use of beta emitters ($_{20}Ca^{45}$, $_{81}Tl^{206}$, $_{38}Sr^{89}$). Beta radiation is already noticeably absorbed by relatively thin foils, therefore a change in the thickness of the foil will immediately affect the absorption of the beta rays,

which in turn will be recorded by Geiger-Müller counters.

The remarkable thing is that the thickness of the foil can be determined without direct contact with the foil itself (Fig. 64). Using a Geiger-Müller counter it is possible not only to note variations in the thickness of the foil, but also automatically to actuate a device that changes the degree of compression to keep the thickness of the foil uniform.

Sometimes the task is to retain not the thickness of the object itself but of a coating being deposited on it. This is often the case in printing or in the textile industry. In the production of artificial silk, an essential operation is coating the thread with a special substance, sodium oleate. If the thread receives a uniform coating, the colour will be uniform. If, however, there is a lack of uniformity in the coating, the colour will not be uniform and the article will have to be rejected. To eliminate this type of defect, a radioactive sodium-labelled admixture is added to normal sodium oleate and a Geiger-Müller counter is placed next to the thread emerging from the bath. The instant the thickness of the coating deviates from standard, the counter registers the change in radioactivity. The counter signals will then actuate the apparatus that regulates the speed of the thread through the bath. If the coating becomes thicker than standard, the speed of the thread will be increased, resulting in a thinner coating.

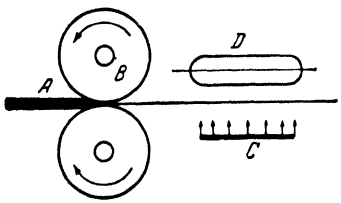


Fig. 64. Varying foil thickness by means of a Geiger-Müller counter.
A — foil; *B* — rolls; *C* — beta-ray source; *D* — counter.

Tracer atoms are important in chemistry where they have found numerous applications. Through their use it is possible to control the completeness of different chemical manipulations (precipitation, washing, etc.), to find ways of refining technological processes, and to automatize chemical purification and separation processes. The use of an apparatus

that automatically follows the course of chemical processes can lead to huge economies.

Tracer atoms permit controlling the reliability of chemical analysis. Particularly important is the so-called *activation analysis*. The essence of the activation analysis is this. If the substance in question is irradiated by a beam of neutrons, a portion of the atoms of stable isotopes in the given material capture neutrons and convert into radioactive isotopes. If one establishes (by the nature of the radiation) what radioactive isotopes are formed, it is possible to get some idea about the presence of the admixtures of different elements in the given substance.

The activation analysis allows of detecting minute impurities. In some substances, an essential part is played by the presence of an infinitesimal quantity of admixtures that are at times expressible in millionths of a per cent. Such, for example, are semiconductors (germanium, silicon, etc.) which are used in rectifiers, photocells, and other important devices. The presence (in semiconductors) of certain impurities in quantities that are absolutely undetectable by ordinary chemical procedures, affect appreciably the physical and chemical properties and make these materials absolutely useless. Only by means of the activation method has it been possible to obtain pure semiconductors.

Thick layers of metal may be examined by the gamma radiation of cobalt-60 and certain other radioactive sources to detect hidden flaws. This radiation has been successfully used in the treatment of many diseases including certain malignant tumours, thus dispensing with expensive and scarce radium which is used for this purpose.

Large doses of beta radiation are very destructive to microorganisms. This makes possible cold sterilization (that is, without boiling) of foodstuffs. Food irradiated with radioactive rays may be kept in storage for a long time. For instance, apples irradiated with beta rays may be kept in a warm room for three months.

Many chemical processes, which in ordinary conditions do not develop, proceed under the action of an intensive radioactive radiation. It has been established, for example, that gamma-ray irradiation aids the formation of plexiglass. Plexiglass is formed from the molecules of a complex sub-

stance called methyl ether of methacrylic acid. These molecules form into long chains under the influence of high temperature and with the simultaneous action of certain activators. In this process, the molecules find it progressively more difficult to move and the entire mass thickens. However, the formation of long chains continues only up to a definite instant; this makes it difficult to obtain thick plates of plexiglass. Irradiation with gamma rays from radioactive cobalt enables the process of plexiglass formation to proceed without heating and without activating substances, and in this way much longer chains are formed, which is very important.

Gamma-ray irradiation of the finished plexiglass causes gases to appear in it. When heated, a piece of plexiglass previously irradiated with gamma rays shows a marked increase in volume and transforms into a snow-white porous, light penoplast which is remarkable for its heat-insulating properties.

From the above examples it may be seen what multifarious applications tracer atoms have found in the economy and how great is the field of their future employment.

Chapter XIV

THERMONUCLEAR REACTIONS

The Binding Energy per Nuclear Particle

An atomic reactor utilizes the energy liberated in the fission of nuclei. However, the fission process is not the only possible source of atomic energy. There are other ways of obtaining atomic energy. To get some concept of what this is about, let us first of all examine the binding-energy values of different nuclei.

We already know that when several particles combine into a nucleus, an energy is released that is equivalent to the binding energy. A nucleus always possesses less energy than the sum of the energies of the individual free particles that comprise it. The more the energy that is released in the formation of a nucleus, the more stable is the nucleus, and the more energy is required to break it up into its component parts. When analyzing the properties of atomic nuclei it is convenient to employ the so-called *specific binding energy*, or, in other words, *the binding energy value per nuclear particle*. Since the total number of particles in the nucleus is equal to the mass number A, the specific binding energy w and the binding energy of the nucleus W are related by the simple equation

$$w=\frac{W}{A}.$$

The values w and W differ in different nuclei. A correlation of the values of w enables one to determine whether energy in a given nuclear transformation will be released or absorbed. Since w characterizes the energy evolved in the formation of the nucleus, it is obvious that if we transfer the nuclear particles from one nucleus with a specific binding energy w_1 to another nucleus with a binding energy $w_2>w_1$, there will

occur a release of energy that is equivalent to the product of the number of transferred particles and the difference (w_2-w_1). If, however, $w_2<w_1$, then the transfer of each particle into a new nucleus will require an average expenditure of energy equivalent to (w_1-w_2). For this reason, *the transition of nuclear particles into a new nucleus with a greater specific bind-*

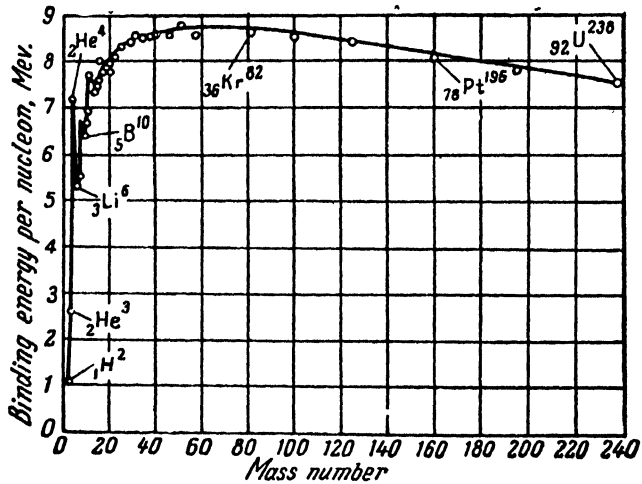


Fig. 65. Specific binding energy of atomic nuclei.

ing energy will be accompanied by a release of energy, the reverse transition will result in absorption of energy.

At present, the magnitude of the binding energy has been established for a very large number of nuclei, and it is therefore possible to determine which nuclear transformations are energetically profitable.

Fig. 65 shows a curve of the specific binding energy as a function of the number of particles (nucleons) in the nucleus. A study of this curve permits of drawing several important conclusions:

1. There is a difference in the magnitude of the specific binding energy of light, medium and heavy nuclei. The most stably bound nuclei contain 100 to 150 nucleons. The specific binding energy of such nuclei is from 8.4 to 8.6 million electron-volts.

2. The heavy nuclei, such as uranium and thorium, have a specific binding energy in the neighbourhood of 7.5 million electron-volts, which is less than that of medium nuclei. This is why energy is liberated when heavy nuclei are converted into medium-weight nuclei. A transformation of this type occurs when a heavy nucleus undergoes fission into two fragments. In this act, the specific binding energy diminishes by 0.9-1.0 million electron-volts, and since a uranium nucleus contains 235 particles the liberated energy comes to approximately 200 million electron-volts.

3. The specific binding energy of light nuclei is also less than that of the medium nuclei. For this reason, *the fusion (synthesis) of light nuclei should result in an energy release.*

The Energy Liberated in Nuclear Fusion

Let us examine cases of the union of different nuclei. Let us suppose that the following transformation has taken place:

$$_8O^{16} + _8O^{16} \longrightarrow _{16}S^{32}$$

or in words, the fusion of two nuclei of oxygen-16 with the formation of a nucleus of sulphur-32. The mass of an atom of sulphur equals 31.982 atomic units, and the mass of each of the oxygen atoms is 16 atomic units. Consequently, this type of fusion should result in the liberation of roughly 18 million electron-volts energy. This energy is of course much less than that released in the fission of a nucleus of uranium. But one must bear in mind that the mass of two oxygen nuclei is many times less than the mass of a uranium nucleus, and that if one relates the released energy not to one nucleus but to an identical weight of "fuel," the difference between the uranium fission energy and the oxygen fusion energy will not be so marked. The energy released in the nuclear fusion of one gram of oxygen will amount to 70 per cent of the energy liberated in the fission of one gram of uranium-235.

Let us now suppose that the following transformation occurs:

$$_{11}Na^{23} + _{10}Ne^{22} \longrightarrow _{21}Sc^{45}$$

From the magnitude of these nuclear masses it follows that an energy of 26 million electron-volts should be released in this transformation. But when calculated per gram it appears that this reaction releases just as much energy as in the fusion of oxygen nuclei.

The foregoing examples show that in the fusion of light nuclei there is released an appreciable quantity of energy, comparable to the energy produced in the fission of heavy nuclei. But the process of nuclear fusion is a highly improbable reaction inasmuch as it requires a certain energy to overcome the electrical forces of repulsion resulting from the large charges of the nuclei. To overcome these forces, oxygen nuclei must possess a kinetic energy of the order of 10 million electron-volts. The kinetic energy of neon or sodium nuclei must be still greater, since their nuclear charges exceed those of oxygen.

Of course, modern acceleration techniques make it possible to accelerate oxygen nuclei to an energy of 10 million electron-volts. However, it is far from profitable to use these machines to obtain energy because the overwhelming majority of such nuclei dissipate their energy before approaching another nucleus close enough for fusion.

Much more favourable is the situation with the fusion of the lighter nuclei, between which the electrical forces of repulsion are less. Let us suppose that two deuterons have fused into one helium nucleus:

$$_1D^2 + {}_1D^2 \longrightarrow {}_2He^4$$

This transformation should liberate an approximate energy of 24 million electron-volts, which is exactly as much as is released in the fusion of the nuclei of neon and sodium. However, the weight of our nucleons is roughly equal to four atomic units, while the weight of $_{11}Na^{23}$ and $_{10}Ne^{22}$ equals 45 atomic units, which is 11 times as much. If we relate the liberated energy to unit weight of the "fuel," it turns out that considerably more energy is released in the fusion of two deuterons than in the fusion of oxygen nuclei or neon and sodium nuclei, or in the nuclear fission of uranium.

The energy released in the fission of one gram of uranium —

235 is roughly equivalent to 22,000 kilowatt-hours, while that released in the fusion of deuterons into helium nuclei is 160,000 kilowatt hours. A still greater energy would be produced in the formation of helium by the fusion of four protons: 176,000 kilowatt-hours from one gram of hydrogen.

This comparison of the fission energy of uranium and the fusion energy of hydrogen nuclei into helium nuclei shows that the latter process is energetically more profitable. However, once nuclear fission has been established (given the condition $npk \geqslant 1$) the process will continue of itself. Contrast this with the fact that in the fusion of every two nuclei of deuterium or of four protons it is necessary to overcome their mutual repulsion. The question arises as to whether it is possible to establish conditions in which fusion of hydrogen nuclei will take place spontaneously.

Such conditions appear to be realizable.

Thermonuclear Reactions

The electric forces of repulsion acting between nuclei prevent their fusion. But fusion may take place if the nuclei possess a kinetic energy large enough to overcome the repulsive forces. And even when the energies of the interacting nuclei are slightly less the fusion process is possible, but by far not in every collision. A given nucleus will have to collide a large number of times before it fuses with another nucleus.

The process of the fusion of nuclei that have a small kinetic energy is statistical in character, which means that it is impossible beforehand to determine in precisely what collision the nuclei will fuse. On the average, fusion will occur after a certain definite number of collisions. We may therefore characterize such a process by means of a so-called *probability of penetration.* If the penetration probability is small the fusion of nuclei upon collision will occur so rarely that a tremendous number of collisions will be required before fusion of any two nuclei takes place. The probability of nuclear fusion is strongly dependent on the kinetic energy of the nuclei, and it shows a marked rise with energy.

An idea of the magnitude of this probability may be gained from Table XII for the case of fusion of two nuclei of heavy hydrogen into a helium nucleus.

Table XII

Kinetic energy of deuteron, electron-volts	Fusion probability	Kinetic energy of deuteron, electron-volts	Fusion probability
100	10^{-60}	2,500	10^{-12}
400	10^{-30}	10,000	10^{-6}
900	10^{-20}	40,000	10^{-3}
1,600	10^{-15}		

The tabulated data show that the fusion probability of deuterons is rather appreciable even at relatively small energies. For example, at an energy of 10,000 electron-volts a nuclear fusion will occur per million collisions on an average. Despite the fact that this energy is small when compared with the energy released in the formation of a helium nucleus (24 million electron-volts) still it is not profitable to accelerate ions of heavy hydrogen to accomplish the reaction

$$_1D^2 + {}_1D^2 \longrightarrow {}_2He^4$$

It has already been pointed out, that the ionization losses of charged nuclei are too big, and when ions traverse a substance containing atoms of heavy hydrogen they lose their energy before an opportune moment appears for two deuterons to fuse.

But heating may be employed to impart energy to the deuterons. It is a well-known fact that an increase in temperature causes a rise in the kinetic energy of atoms and molecules. The mean kinetic energy of atoms and molecules at a temperature of 20°C. is small, being only $\frac{3}{80}$ of an electron-volt. To impart to the molecules of a gas, liquid or solid a mean kinetic energy of one electron-volt, they must be heated to 7,500 degrees. But at such an energy the probability of nuclear fusion is so infinitesimal (10^{-600}) that such reactions simply do not occur. In order to communicate to hydrogen nuclei an energy sufficient for their synthesis, the substance must be heated to a much higher temperature.

If heavy hydrogen is heated to one million degrees the situation becomes essentially different. At this temperature the mean kinetic energy of the deuterons is roughly 130 electron-volts, and the probability of their fusion at this energy is still insignificant (approximately 10^{-50}). However, 130 electron-volts is only the mean kinetic energy of the nuclei. A portion of the nuclei will possess considerably greater energies. And a tiny fraction of the deuterons (10^{-8}) will have an energy within the range 1,600 to 2,500 electron-volts. The probability of deuteron fusion at this energy is no longer very small—from 10^{-15} to 10^{-12}. If we take into account the fact that at a temperature of one million degrees each atom of the substance will experience approximately 10^{10} collisions per second and that there are 3×10^{26} deuterons in one kilogram of heavy hydrogen, it will be clear that in these conditions there will be a large number of cases of the formation of helium by the fusion of two deuterons. Estimates show that at a temperature of one million degrees the fusion of one kilogram of deuterons will produce every second an energy equivalent to about 100 kilowatts. At a temperature of 5-6 million degrees the entire kilogram of deuterons will "burn up" in a fraction of a second with the release of 150 million kilowatt-hours.

Thus we see that at sufficiently high temperatures the fusion reaction of deuterons is possible. At several million degrees a highly effective reaction is

$$_1H^1 + {}_3Li^7 \longrightarrow 2\,{}_2He^4$$

which also releases a considerable energy (about 17 million electron-volts).

Nuclear reactions that proceed at high temperatures are commonly called *thermonuclear reactions*. The following are examples of thermonuclear reactions:

$$_1D^2 + {}_1D^2 \longrightarrow {}_2He^4$$
$$_1D^2 + {}_3Li^7 \longrightarrow 2\,{}_2He^4 + {}_0n^1$$

We have established that at a temperature of the order of a million degrees, thermonuclear reactions can develop quite effectively. Does nature ever provide us with such conditions? It turns out that precisely such high tempera-

tures are predominant in stellar interiors. This is why thermonuclear reactions occur there.

The problem of the energy sources of the sun and stars was for a long time a puzzle that engaged the inquisitive minds of scientists. Why do the stars shine? Why does the sun, which is one of the relatively small stars, shine? What is the source of its energy?

The sun is known to radiate collosal quantities of energy. The power of solar radiation is expressed by the stupendous number of 3.5×10^{23} kilowatts, which is a thousand million times that of what a hundred million Bratsk hydropower stations (this station is now under construction on the Angara River and will develop 3,400,000 kilowatts) could produce. Where does this truly gigantic energy output come from?

Simple calculations show that ordinary sources cannot be the cause of such an intense liberation of energy. One of the most widespread sources of energy on earth is the process of combustion. The combustion of one kilogram of coal releases about 8,000 large calories. If we should assume that the sun is composed entirely of carbon and an appropriate quantity of oxygen (necessary for full combustion), the combustion of all this carbon would produce 4×10^{33} large calories. Given the degree of radiation mentioned above, the sun radiates annually a quantity of heat equal to 2.6×10^{30} large calories. Hence, if the source of solar energy were the combustion of carbon, the sun would burn up completely in just over one thousand years, whereas we know very well that the earth and our entire solar system have existed for at least several thousand million years. This means that the radiation of stars is caused by considerably more powerful sources of energy than ordinary chemical reactions. These are thermonuclear reactions. They are one of the most important sources of stellar energy.

Apparently, during certain stages in stellar development the energy lost by a star is entirely created by thermonuclear reactions that occur in its interior. What thermonuclear reactions form the source of the sun's energy? This question was answered by Bethe.

Astronomers have estimated that the temperature inside the sun rises to 20 million degrees. If there were heavy hydrogen in the solar interior, helium would be produced at this

temperature so rapidly that the sun would explode. The reaction

$$_1D^2 + _1H^1 \longrightarrow _2He^3$$

could fully supply the energy the sun loses even with an interior temperature of only 400,000 degrees. Apparently, neither can the reaction

$$_3Li^7 + _1H^1 \longrightarrow 2_2He^4$$

be a source of solar energy, for it also develops too violently at 20 million degrees of temperature. Apparently, the foregoing thermonuclear reactions determine the radiation of stars during their early stages of development.

At a temperature of the order of 20 million degrees, thermonuclear reactions of the so-called carbon-nitrogen cycle should be capable of proceeding with sufficient intensity.

What does the carbon-nitrogen cycle consist of? This cycle consists of a whole series of thermonuclear reactions. It begins with a transformation that occurs when a proton enters a nucleus of carbon-12. The result of this reaction is nitrogen-13. This isotope is radioactive and decays with the emission of a positron, producing the stable isotope carbon-13. The second stage of the carbon-nitrogen cycle involves a carbon-13 nucleus. A proton enters this nucleus to produce a nucleus of nitrogen-14, which is stable. The next stage is a thermonuclear reaction with the penetration of a third proton into the nitrogen-14 nucleus to produce the isotope oxygen-15, which is radioactive and decays to nitrogen-15 with the emission of a positron. The last stage of the carbon-nitrogen cycle is a thermonuclear reaction involving the penetration of a proton into a nitrogen-15 nucleus with the production of carbon-12 and helium-4 nuclei.

All these transformations may be written as follows:

$$_6C^{12} + _1H^1 \longrightarrow _7N^{13*} + \text{radiation},$$
$$_7N^{13*} \longrightarrow _6C^{13} + _{+1}e^0,$$
$$_6C^{13} + _1H^1 \longrightarrow _7N^{14} + \text{radiation},$$
$$_7N^{14} + _1H^1 \longrightarrow _8O^{15*} + \text{radiation},$$
$$_8O^{15*} \longrightarrow _7N^{15} + _{+1}e^0,$$
$$_7N^{15} + _1H^1 \longrightarrow _8O^{16*} \longrightarrow _6C^{12} + _2He^4.$$

The result of these transformations is again a nucleus of carbon-12, which initiated the carbon-nitrogen cycle. However, in the process four protons disappear to produce

a nucleus of helium. Consequently, the final result of the carbon-nitrogen cycle is equivalent to the fusion of four protons into a nucleus of helium:

$$4\,{}_1H^1 \longrightarrow {}_2He^4 + 2 \text{ positrons} + \text{radiation}.$$

The over-all total energy released in the carbon nitrogen cycle amounts to 26.8 million electron-volts.

Thus, according to Bethe, the source of solar energy is a transformation of hydrogen into helium which occurs indirectly via the carbon-nitrogen cycle. The quantity of hydrogen in the sun at the present time is, on this theory, sufficient for the production of radiated solar energy for another eighty thousand million years.

Bethe's theory gives a rather good explanation of the origin of solar energy. However, one should not consider the carbon-nitrogen cycle as the sole source of solar radiation. It is possible that in the solar interior there occur other thermonuclear reactions. Our present knowledge is not sufficient for a final solution to the problem of the sources of stellar energy.

The Hydrogen Bomb

The conditions in the interior of stars (high temperatures and pressures) permit the development of thermonuclear reactions. Similar conditions appear for a brief lapse of time during the explosion of an atomic bomb. Here the temperature is in many millions of degrees and the pressure reaches a hundred million tons per square centimetre. In these conditions a thermonuclear reaction can also commence. Inasmuch as the conditions suitable for the development of a thermonuclear reaction exist for a very brief duration, only such thermonuclear reactions will succeed in developing as proceed with extraordinary rapidity. Of the following possible thermonuclear reactions:

$${}_1D^2 + {}_1H^1 \longrightarrow {}_2He^3 + \text{radiation},$$
$${}_1D^2 + {}_1D^2 \longrightarrow {}_1T^3 + {}_1H^1,$$
$${}_1T^3 + {}_1H^1 \longrightarrow {}_2He^4 + \text{radiation},$$
$${}_1T^3 + {}_1D^2 \longrightarrow {}_2He^4 + {}_0n^1,$$

only the last one develops with sufficient speed (of the order of 10^{-6} second). This was the reaction employed in building the hydrogen bomb.

The hydrogen bomb has a very strong casing, inside of which is an ordinary atomic bomb and a vessel containing deuterium and tritium. The atomic explosion creates the conditions necessary for the development of a thermonuclear reaction in hydrogen and "ignites" the hydrogen bomb.

The hydrogen isotope of mass 3, tritium ($_1T^3$), which is a component of the hydrogen bomb, is not stable. It decays with a half-life of 12 years. Tritium may be obtained in the following reactions:

$$_3Li^6 + {}_0n^1 \longrightarrow {}_2He^4 + {}_1T^3,$$

$$_1D^2 + {}_0n^1 \longrightarrow {}_1T^3,$$

$$_2He^3 + {}_0n^1 \longrightarrow {}_1T^3 + {}_1H^1,$$

$$_4Be^3 + {}_1D^2 \longrightarrow {}_1T^3 + 2{}_2He^4,$$

$$_1D^2 + {}_1D^2 \longrightarrow {}_1T^3 + {}_1H^1.$$

The first three reactions occur in atomic reactors, and the latter two in cyclotrons.

Hydrogen bombs are more powerful than atomic bombs. The power of an atomic bomb is restricted by the critical mass of the fissionable nuclear explosive. The critical mass puts a limit on the quantity of uranium or plutonium which may be used to charge the bomb. Hydrogen bombs have no critical size. Therefore, the power of a hydrogen bomb is limited only by technical feasibility (the amount of tritium, the conditions of transportation, etc.).

Hydrogen bombs have been developed in the U.S.A. and in the Soviet Union. But the Soviet Union is not conducting an aggressive policy and does not threaten anyone with atomic or hydrogen weapons. The atom weapon is produced in the U.S.S.R. only as a means of self-defence. The Soviet nation is an indefatigable and consistent fighter for prohibition of all types of weapons (including atomic and hydrogen bombs) of mass extermination of human beings, for stopping the production of those bombs and for destroying all existing stocks of bombs.

Controlled Thermonuclear Reactions

Test explosions of the hydrogen bomb have shown that a thermonuclear reaction could be produced artificially. When a hydrogen bomb is detonated, a tremendous amount of energy is released within a split second. If it were possible to reduce the speed of the energy release in a thermonuclear reaction by controlling the latter, the energy liberated could be used for purposes of peace. A noble task now confronts the scientists of the whole world, that of bringing thermonuclear reactions under control.

A controlled thermonuclear reaction will place at the service of mankind limitless supplies of energy. At present, the principal energy resources are coal, petroleum, and peat that have accumulated in the earth over the ages. With the present tempestuous development of industry, energy is expended so rapidly that the time is not far off, relatively speaking, when the supplies of petroleum, coal and peat will be exhausted. The realization of a chain nuclear reaction unearthed new types of natural fuel—uranium and thorium. The available compounds of uranium and thorium contain energy reserves that exceed by 10 to 20 times the energy contained in the now known deposits of petroleum, coal and peat. Uranium and thorium, of course, augment appreciably our energy resources. New possibilities open up with their utilization in the power industry. However, these types of fuel, too, will be consumed in the foreseeable future.

The utilization of energy released in thermonuclear reactions will revolutionize the entire field. The realization of a controlled thermonuclear reaction will once and for all time solve the power problem, for the raw material of a thermonuclear reaction—hydrogen—is found in tremendous quantities everywhere.

To bring a thermonuclear reaction under control is an exceedingly difficult problem. In this field, Soviet scientists are engaged in very large-scale and fruitful research. In a lecture delivered at the British atomic centre at Harwell, I. V. Kurchatov gave an account of some of these investigations.

In the U.S.S.R. Academy of Sciences, L. A. Artsimovich and M. A. Leontovich have supervised studies that indicate the possibility of obtaining (by means of a gas discharge) a temperature of the order of a million degrees. This is the first time that such a high temperature has been obtained in laboratory conditions.

In the case of significant rises in temperature, there may develop tremendous pressures in the substance. For this reason, the method of discharges in a gas at room temperature and reduced pressure was selected for the laboratory experiments. The employment of a discharge in a rarefied gas relieved scientists of the necessity of building apparatus with extremely thick walls to withstand the enormous pressures. An electric discharge (the appearance of charged particles, ions and electrons) originates in a rarefied gas when a sufficient voltage is applied. The greater the number of ions and electrons produced in the gas, the bigger the electric current that passes through the gas. The current passage is accompanied by the generation of heat. The temperature of the gas rises. However, it is not possible to raise the temperature of the gas very high for the particles in the gas make encounters with the walls of the chamber inside which the discharge takes place, and thus heat them. At a temperature close to a million degrees this heat loss is so great that without proper heat insulation of the particles (participating in the discharge) from the walls of the discharge chamber, it becomes impossible to actually reach one million degrees.

A. D. Sakharov and I. E. Tamm found a way to produce heat insulation of the gas plasma*. What they proposed is simple. We know that when charged particles enter a magnetic field their trajectories curve. A strong magnetic field may compel charged particles to move along closed curves, for instance in circles. The stronger the magnetic field the less the diameter of the circle described by the charged particles. If we place a gas plasma in a strong magnetic field, it is possible to make the ions

* The plasma is a medium of positively charged ions and electrons. It is produced in a gas discharge and is a good conductor of electricity.

and electrons move in a small volume. A strong magnetic field will not allow the ions to approach the walls of the vessel, and in this way the gas plasma becomes insulated from the walls of the discharge chamber.

The gas plasma, as we have already pointed out, is a good conductor of electricity; it can pass big currents. But magnetic fields appear around electric currents. If a current passing through the plasma is sufficiently big, it will create a strong magnetic field and then both problems will be solved at one stroke: with a huge current traversing the plasma, a large quantity of heat will be generated in it; on the other hand, due to the strong magnetic field, the particles of the plasma will find themselves well insulated from the walls of the discharge chamber and the plasma will be able to heat up to a high temperature. Thus, the problem is to pass a large electric current through the discharge chamber. This is what L. A. Artsimovich and his co-workers succeeded in doing. They passed through the chamber momentary (pulse) currents up to two million amperes. Even at currents of several hundred thousand amperes they noticed that due to the influence of the magnetic field, the gas plasma begins to pull away from the walls of the containing vessel and to draw out into a narrow column. With a current of a million amperes, the temperature in this column reaches a million degrees.

Undoubted progress has been made towards the establishment of a controlled thermonuclear reaction; we have obtained, in controlled fashion, temperatures of the order of a million degrees, which are necessary for the development of a thermonuclear reaction. It may be hoped that in the relatively near future a controlled thermonuclear reaction will be achieved and that Soviet scientists will make their worthy contribution to the solution of this exceedingly important problem.

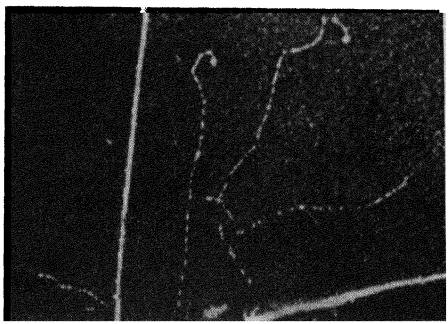


Fig. Ia. Cloud-chamber photograph showing the thick straight lines of alpha particles and the thin bent lines of slow electrons.

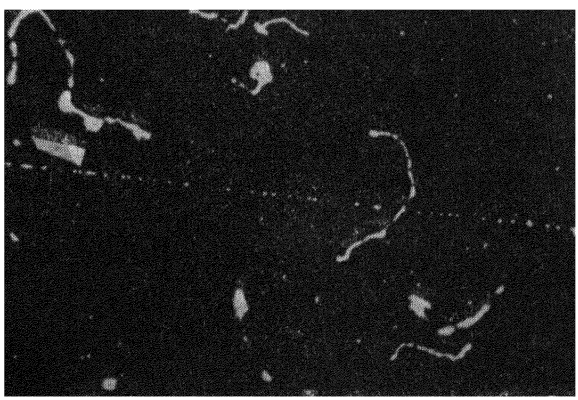


Fig. Ib. Cloud-chamber photograph. The bent lines are the tracks of slow electrons, and the straight dashed line is the track of a high-energy electron.

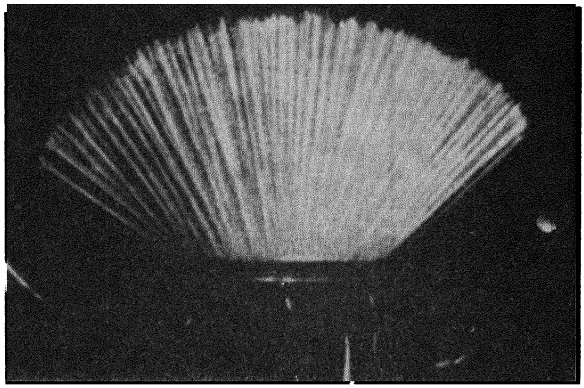


Fig. II. Alpha-particle tracks in a cloud-chamber photograph. It is evident from the picture that all alpha particles ejected from the radioactive substance cover practically the same distance in the chamber.

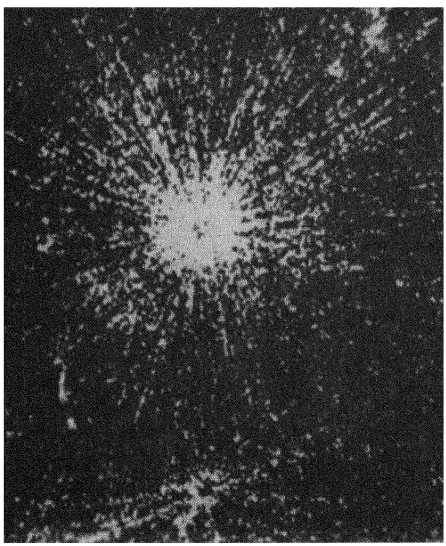


Fig. III. A microphotograph of the tracks of radium radiation in the light-sensitive layer of a photographic plate.

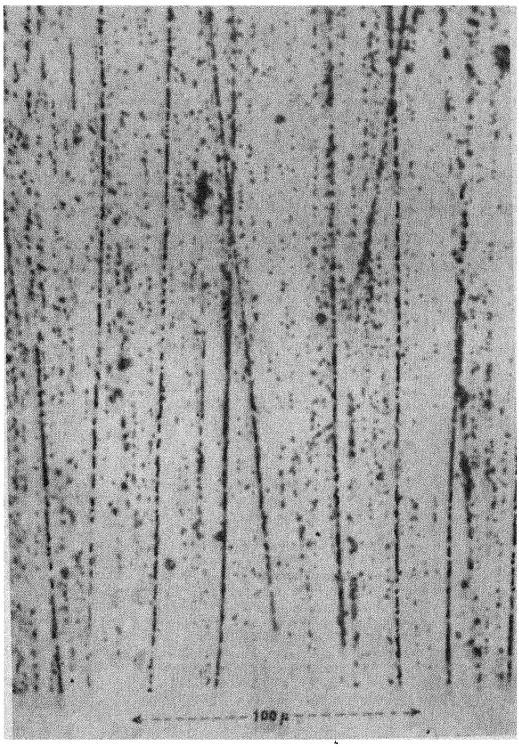


Fig. IV. Tracks of alpha particles and deuterons from a 184-inch cyclotron; the particles enter the emulsion nearly parallel to its surface. Both types of particles have the same speed. The difference in their specific ionization is clearly visible: the alpha-particle tracks are thick and the tracks of deuterons are thin. The initial energy of the alpha particles is 200 million electron-volts, that of the deuterons, 100 million electron-volts.

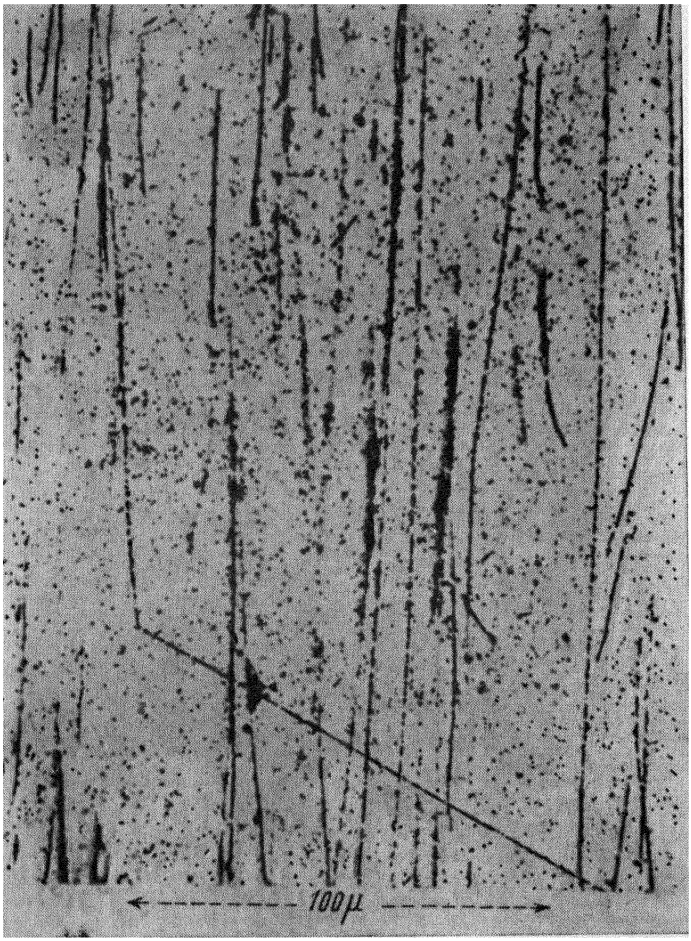


Fig. V. The tracks of protons and alpha particles in a photographic emulsion.

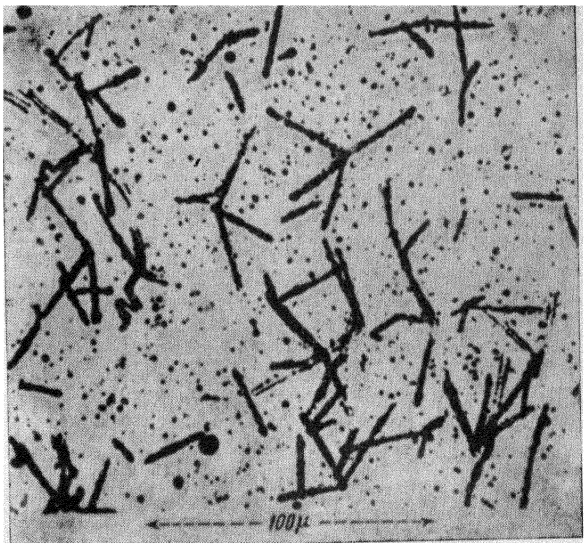


Fig. VI. Alpha-particle tracks in an emulsion. The alpha particles did not impinge on the plate from the side but originated in the emulsion itself, to which a small amount of alpha-emitting thorium had been added. The "stars" which are clearly visible in this photograph are nuclei that undergo a succession of transformations with emission of alpha particles. After being developed the plate was strengthened, so the particle tracks appear thick and very bright.

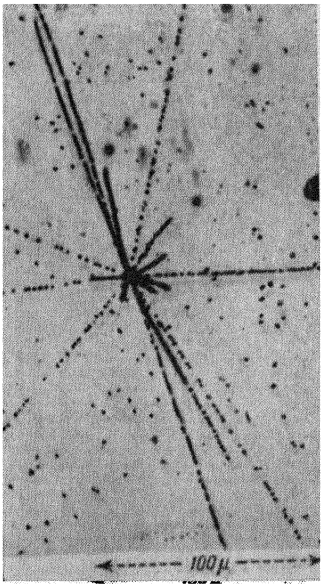


Fig. VII. An explosive disintegration of a nucleus (probably silver) by a cosmic-ray particle. The energy of the particle that initiated the fission was of the order of 100 million electron-volts. It is possible to distinguish the tracks of seven protons, five alpha particles and a certain number of heavier nuclear fragments. The bulk of the particles enter the glass from the emulsion and emerge from the plate; for this reason it was not possible to give an exact determination of their range, and hence, their energy.

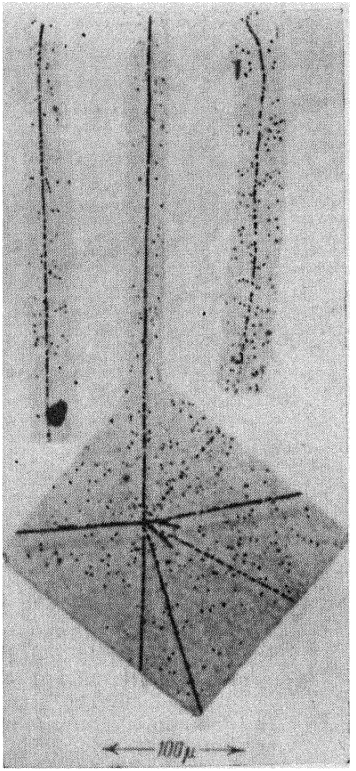


Fig. VIII. The disintegration of a heavy nucleus by cosmic rays and the tracks of a meson (upper right) and a triton (a nucleus of superheavy hydrogen, $_1H^3$) (upper left). The long track going upward from the star is that of an alpha particle.

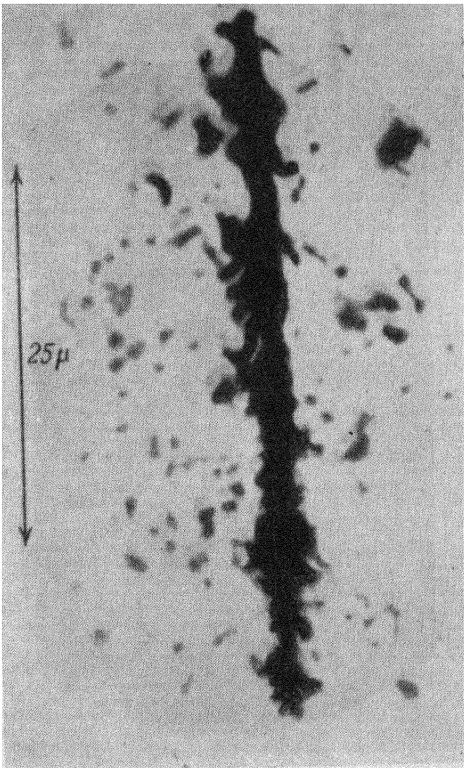


Fig. IX. Microphotograph of the track of a cosmic particle with a large charge ($Z=15$).

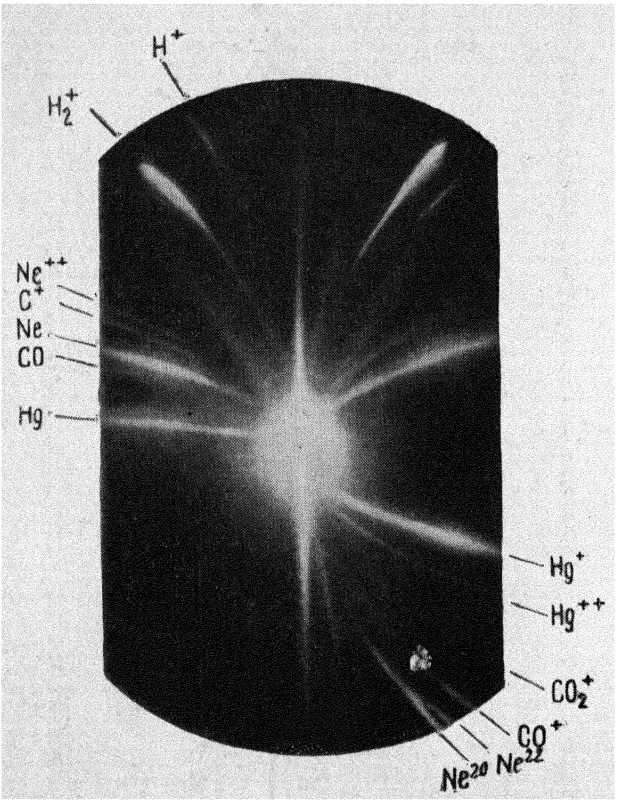


Fig. X. Isotope parabolas obtained by Thomson.

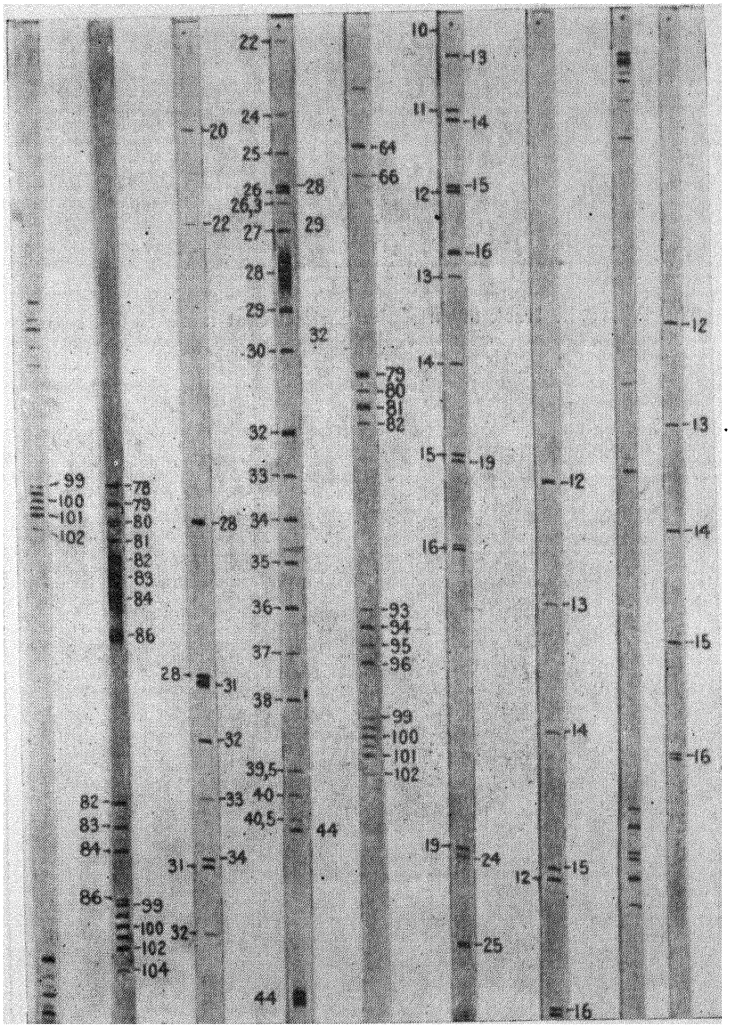


Fig. XI. Mass-spectrograms of a number of elements with mass numbers in the range from 12 to 104. The spectrograms were obtained by Aston.

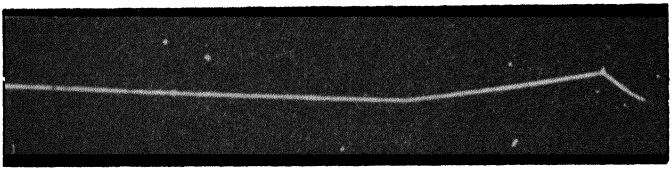


Fig. XII. The track of an alpha particle that has suffered two collisions.

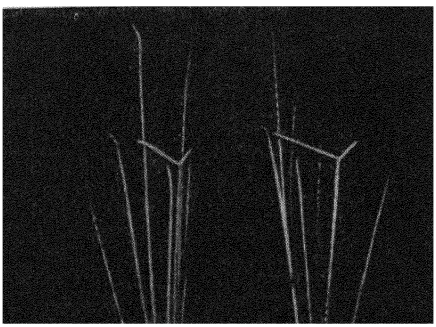


Fig. XIII. Alpha-particle tracks in an oxygen-filled cloud chamber.

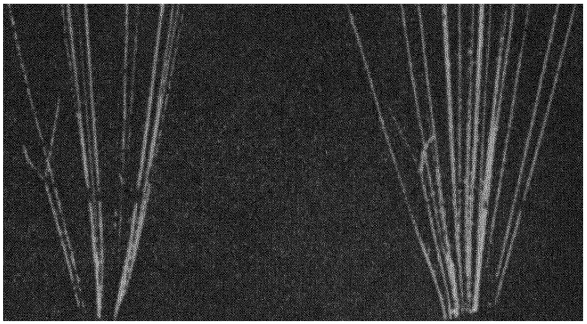


Fig. XIV. Alpha-particle tracks in nitrogen. A fork is seen that was produced by an alpha particle long before coming to the end of its range. The thinner track is that of a proton, the thicker one that of a nucleus which captured the alpha particle.

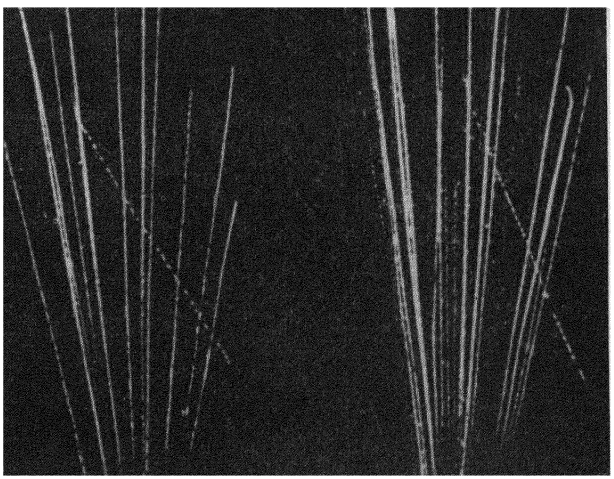


Fig. XV. Disintegration of nitrogen by alpha particles. The track of a proton ejected in a direction opposite to that of alpha particle is visible.

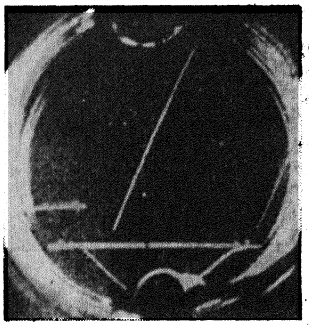


Fig. XVI. Track of proton knocked out of paraffin by a neutron.



Fig. XVII. Track of a helium nucleus set into motion by collision with a neutron.

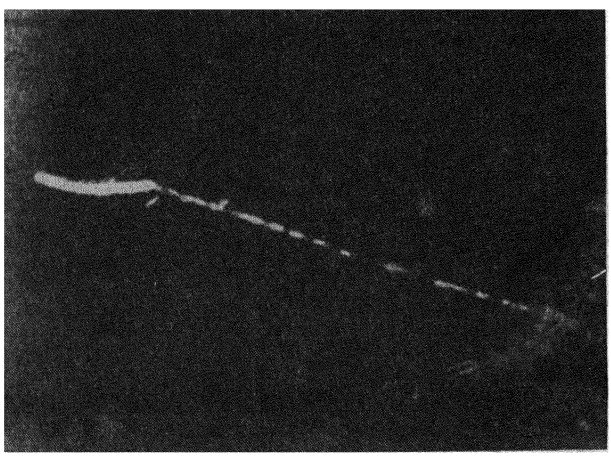


Fig. XVIII. Fission of a nitrogen nucleus by a neutron according to the scheme ${}_7N^{14} + {}_0n^1 \longrightarrow {}_5Be^{11} + {}_2He^4$. The thin track is that of an alpha particle; the thick one is that of a boron nucleus produced in the fission of the nitrogen nucleus.

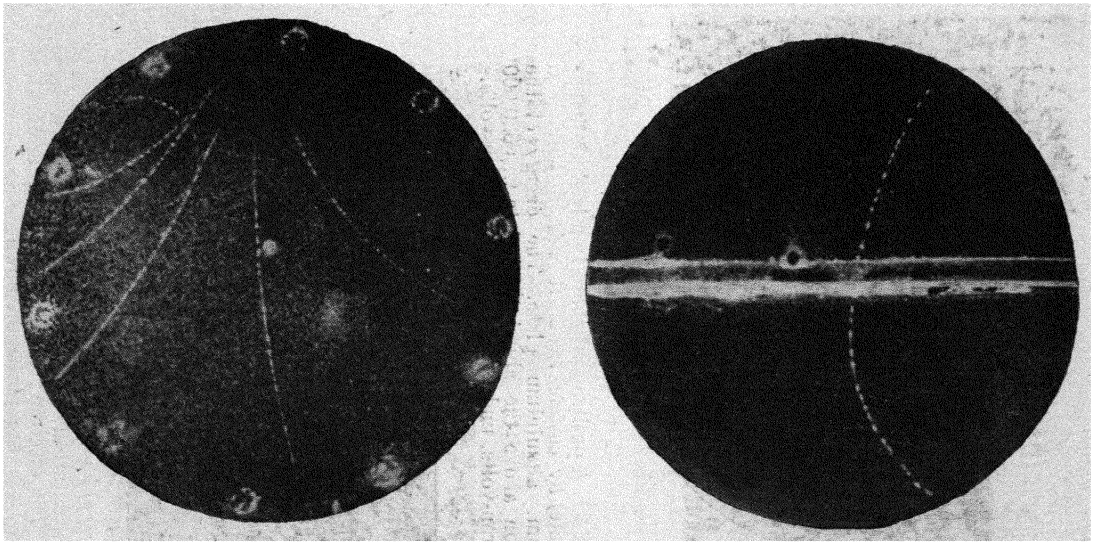


Fig. XIX. Cosmic-ray tracks photographed by Anderson in a cloud chamber placed in a 25,000-oersted magnetic field.

Fig. XX. The track of a cosmic particle traversing a 5-mm. thick lead plate put across a cloud chamber in a magnetic field.

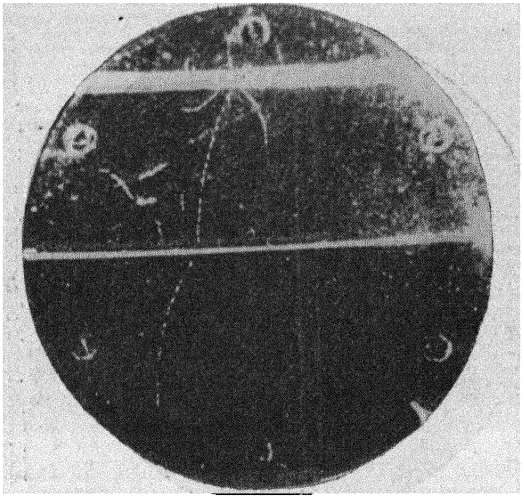


Fig. XXI. A positron produced in a lead plate (upper plate) by cosmic rays. It passed through a 0.5 -mm. aluminium plate. The energy of the positron above the aluminium plate was 820,000 electron-volts, under it, 520,000 electron-volts.

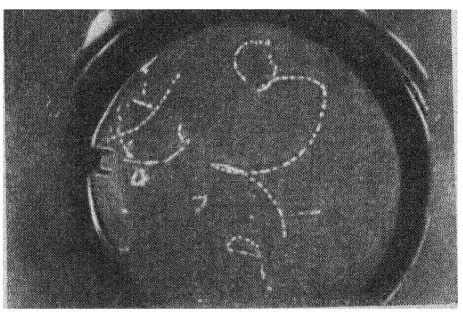


Fig. XXII. A photograph of pair formation in krypton obtained by L. V. Groshev and I. M. Frank. The electron track is deviated upwards, the positron, down.

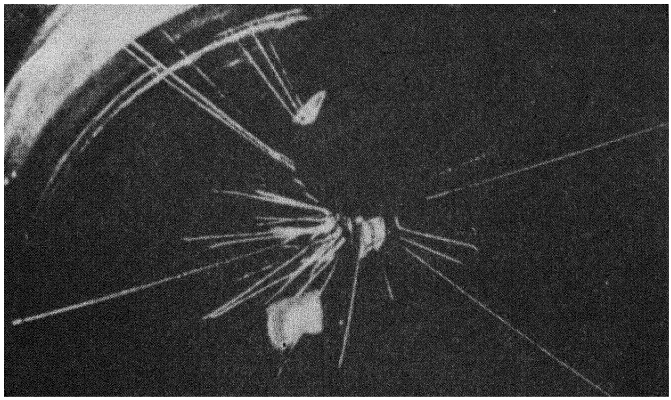


Fig. XXIII. Disintegration of lithium.

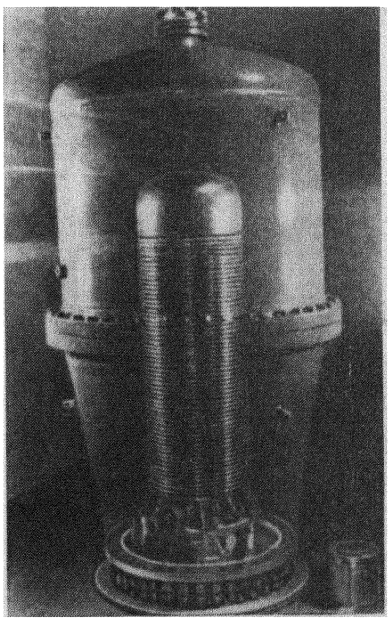


Fig. XXIV. A pressurized electrostatic generator. The picture is composed of two photographs. The first is the tube, the second the casing 3.05 m. long which houses the former.

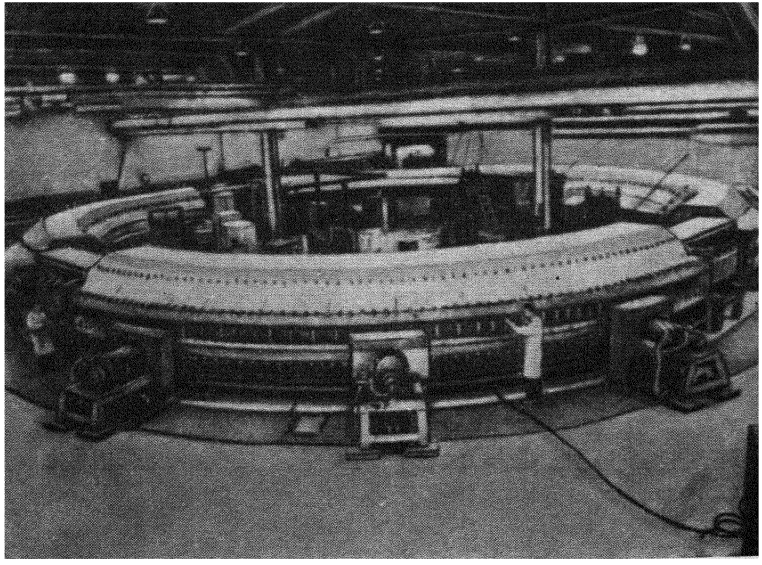


Fig. XXV. General view of the Brookhaven cosmotron.

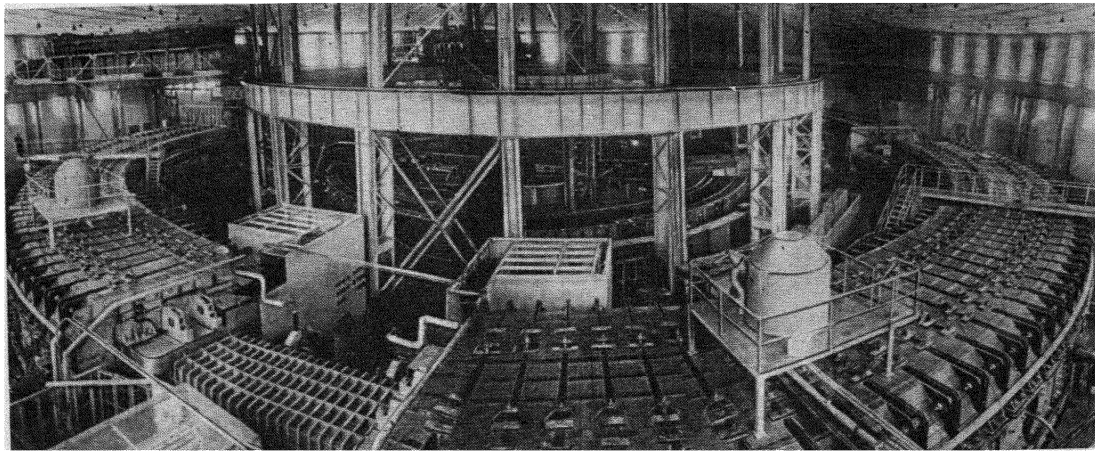
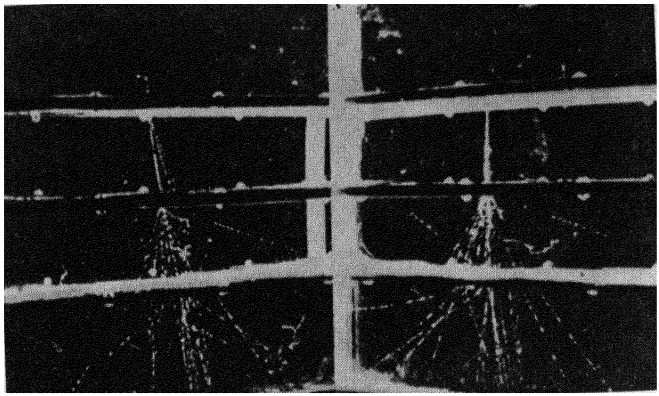


Fig. XXVI. General view of the U.S.S.R. Academy proton synchrotron.



Ftg. XXVII. Shower development in lead plates.

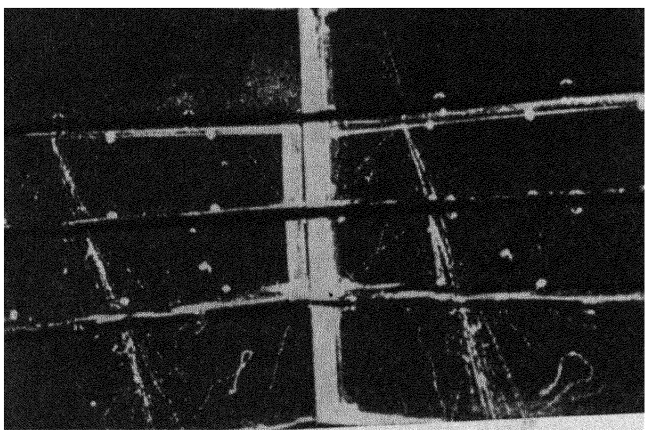


Fig. XXVIII. Shower development in lead plates.

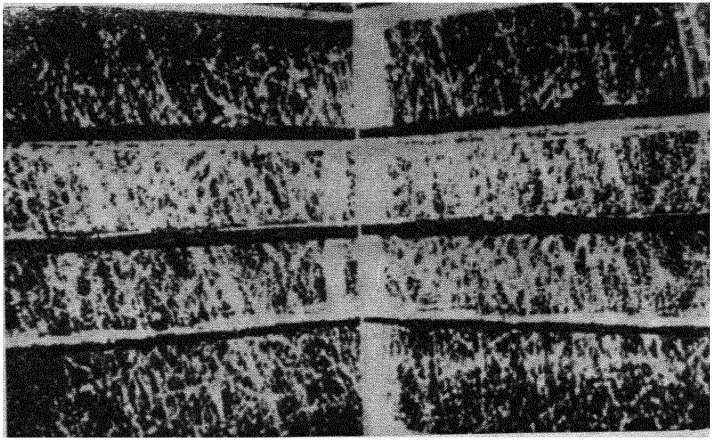


Fig. XXIX. A gigantic shower. The initiating particle possessed over 10^{12} electron-volts.

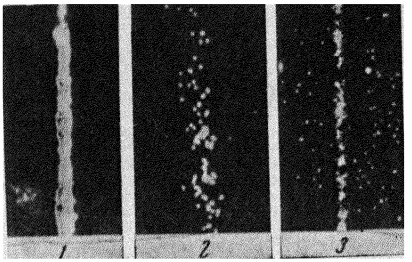


Fig. XXX. Tracks of different particles in a cloud chamber.

1 — Proton track in oxygen; 2— Electron track in hydrogen; 3—Electron track in oxygen.

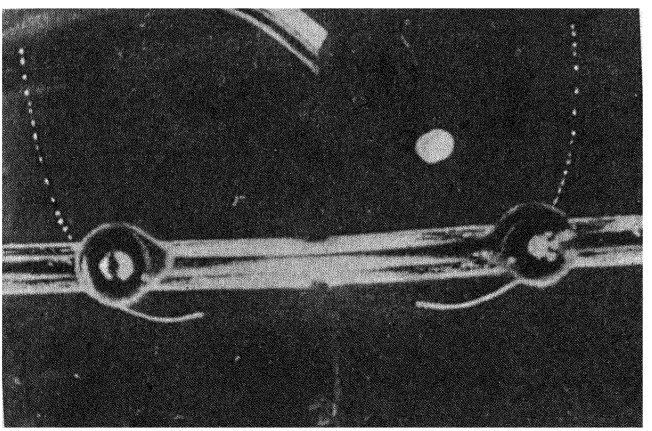


Fig. XXXI. Meson track. The meson passed through a counter located in the middle of the cloud chamber. The chamber was in a magnetic field. This picture was obtained by Anderson and Neddermeyer who found the mass of the particle to be 220 electronic masses.

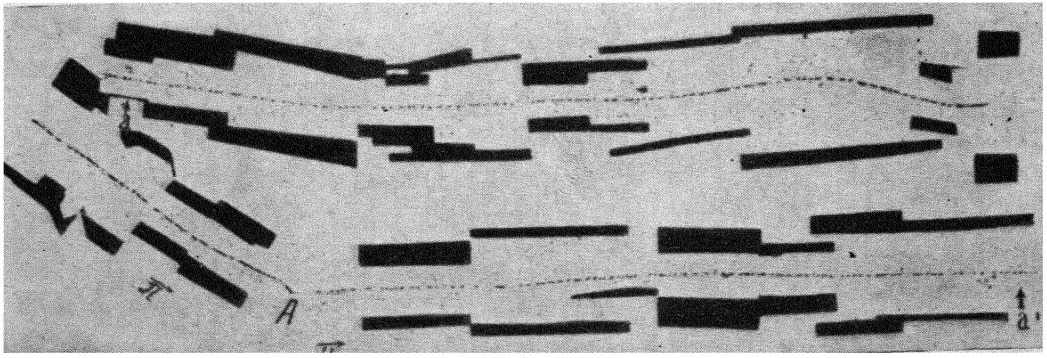


Fig. XXXII. A photograph of the decay of a heavy meson obtained by Powell and Occhialini. The heavy 300-m_e meson (designated as π) is slowed down in the photographic plate. At the end of its range, at point *A*, it disintegrates giving birth to a light meson of mass 200 m_e (designated by μ). For conveniency, the track of the light meson is divided into two parts at point *a*, indicated by the arrow; the end is shown above.

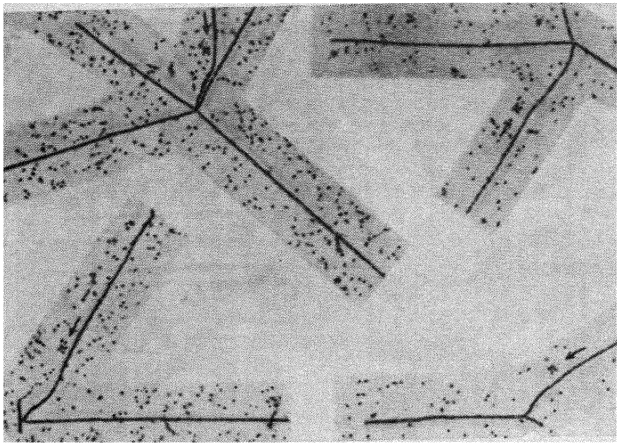


Fig. XXXIII. Tracks in a photographic emulsion showing the decay of light nuclei under the action of π-mesons.

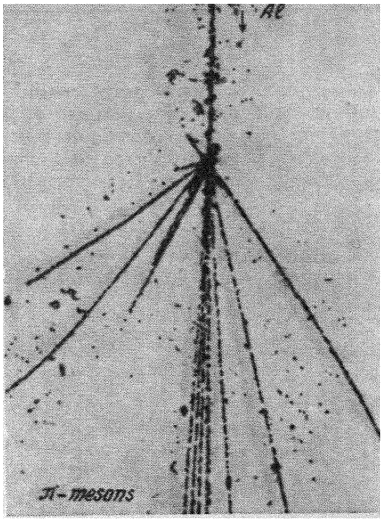


Fig. XXXIV. A primary cosmic particle (aluminium nucleus) has collided with a nucleus in the emulsion. The tracks of individual particles ejected from the nucleus may be seen. Among them are those of mesons.

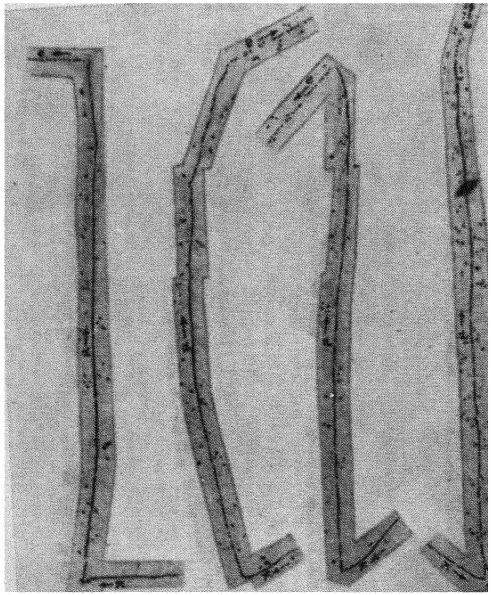


Fig. XXXV. The transformation $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$.

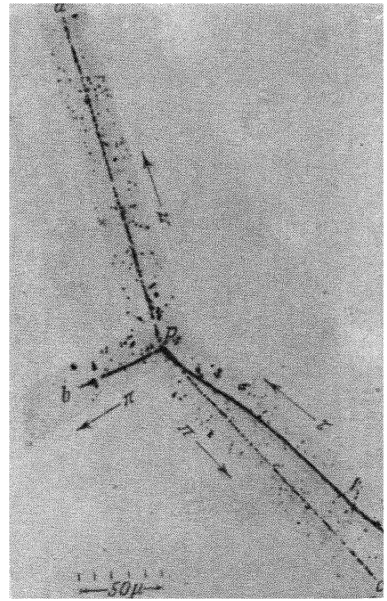


Fig. XXXVI. The decay of a τ-meson into three charged π-mesons.

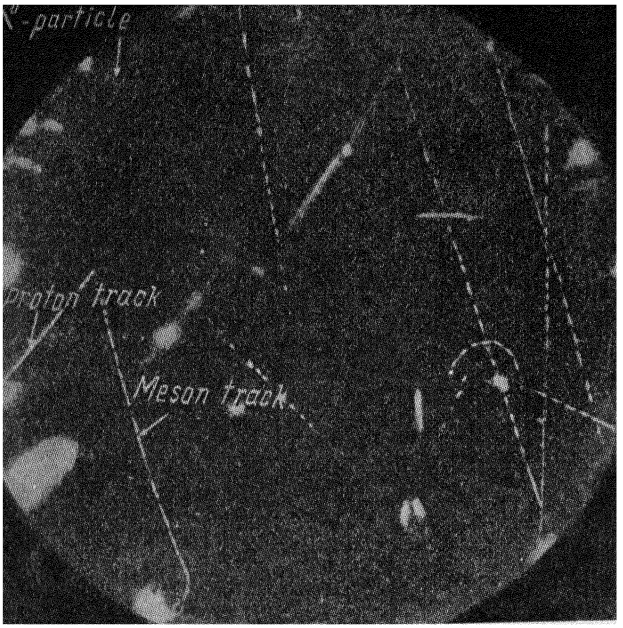


Fig. XXXVII. The picture shows a fork consisting of a proton, and a π-meson. The fork was produced by the transformation of a neutral hyperon, Λ°. The track of the neutral hyperon is not visible in the photograph; its assumed path is indicated by an arrow.

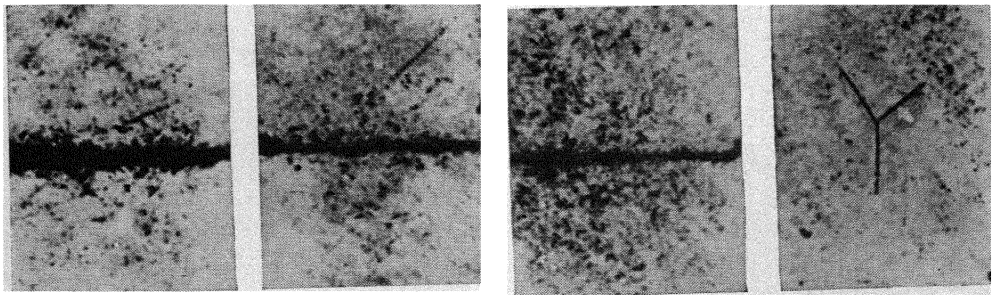


Fig. XXXVIII. Photographs of the tracks of an alpha particle emitted in the decay of thorium and of a cosmic particle with a big charge. The right-hand plate contains the track of an alpha particle. The second plate from the right shows the track of a cosmic particle as it enters the emulsion. The third plate shows the track of the same particle after traversing a 4.5 g./cm.^{2} thick layer of emulsion. The fourth plate is the track of the same particle after traversing a layer of material 9.2 g./cm.^{2} in thickness. The greater the layer the particle traverses, the less energy it retains and the greater is its ionizing capacity.

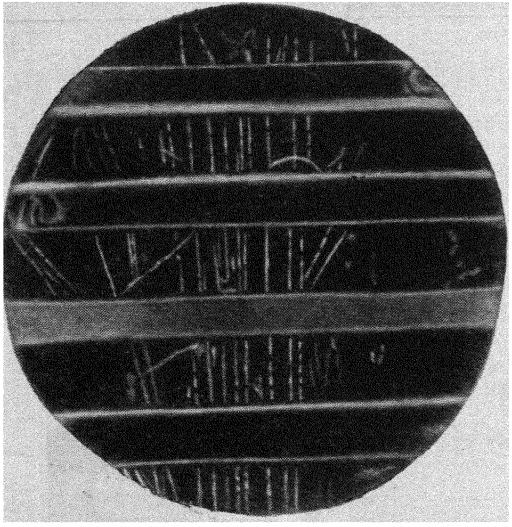


Fig. XXXIX. A shower of particles that have not undergone multiplication.

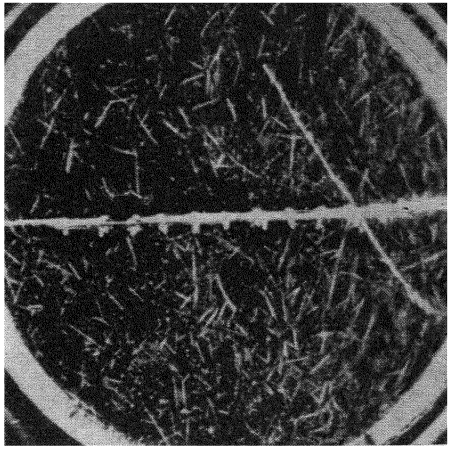


Fig. XL. Fission of uranium induced by neutrons. A thin layer of uranium oxide is deposited on a plate put across the cloud chamber. The long tracks are the trajectories of two fragments formed in the fission process. The fragments shot out in opposite directions. Numerous short tracks were formed in collisions of neutrons with the hydrogen atoms of the chamber vapour.

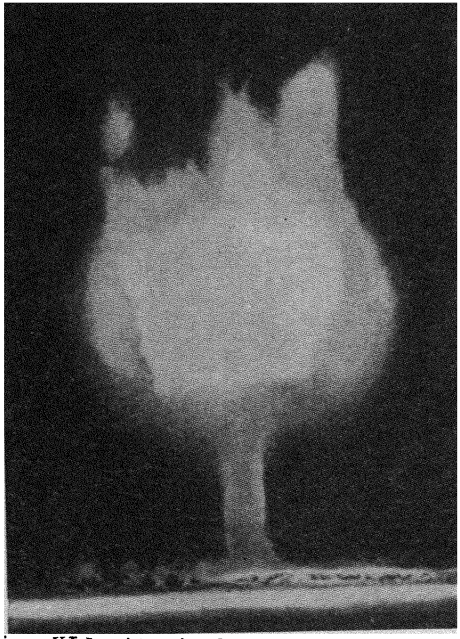


Fig. XLI. Atomic bomb explosion. The ball of fire is visible. The temperature inside the ball of fire is in excess of one million degrees.



Fig. XLII. Dome-shaped cloud that forms in underwater atom-bomb bursts.

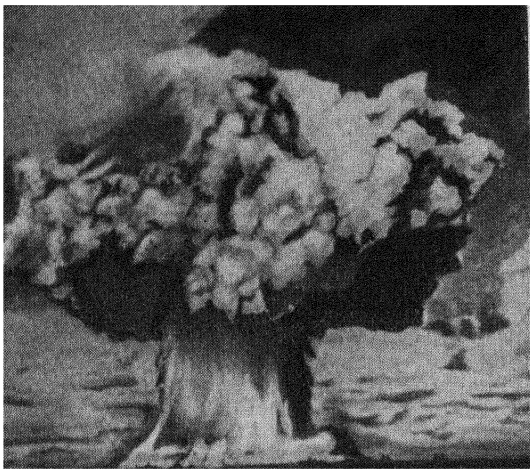


Fig. XLIII. The "plume" and first stages in the development of the base surge in an underwater burst.

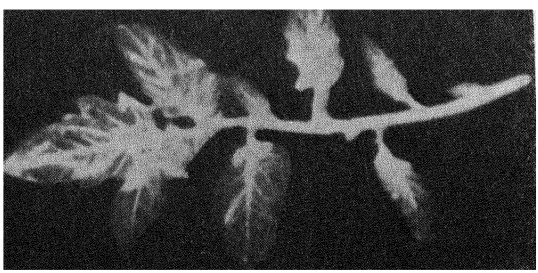


Fig. XLIV. A radioautograph of a tomato leaf. The photograph was produced by placing the leaf on a photographic plate. The plant was fed with radiophosphorus, which accumulated to produce the light areas.

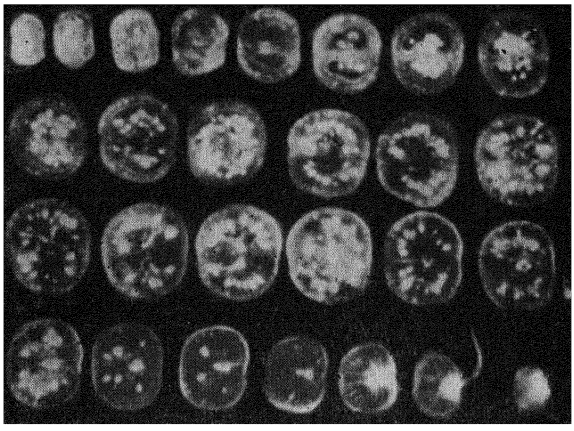


Fig. XLV. A radioautograph of sections of a tomato fed with radioactive zinc chloride. The radioactive zinc is seen to concentrate in the seeds of the fruit.

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