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The World and the Atom

The World and the Atom

by
C. MØLLER
and
EBBE RASMUSSEN

Foreword by
PROFESSOR
NIELS BOHR

London
George Allen & Unwin Ltd

FIRST PUBLISHED IN ENGLISH IN 1940

THE DANISH ORIGINAL
Atomer og andre Smaating
WAS PUBLISHED IN COPENHAGEN
IN 1938
SECOND EDITION, 1939

TRANSLATED FROM THE SECOND
DANISH EDITION BY
GERALD C. WHEELER
AND
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in 11-Point Baskerville Type
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WOKING

Note on the Translation

Mr. J. Robertson, M.Sc., A.Inst.P., has kindly revised my translation. My best thanks are due to him for making many corrections (especially in scientific terms) and for suggestions. The text of the translation has been further revised and very extensively amended by Mr. Bernard Miall, except for a portion for which this was done by Mr. C. A. Furth. The Danish authors have also made certain modifications in their original, enhancing its value.

G. C. W.

Foreword

I BELIEVE that this book will give a wide circle of readers an excellent opportunity of learning something about the wonderful developments in atomic physics in our own day. Our penetration into new worlds hitherto closed to men's eyes has brought to light a wealth of forces in nature of which we had no inkling. At the same time, through the new light thrown on our own position as observers of the world about us, we have won a fresh outlook upon deep problems of knowledge in general.

That the book results from the joint work of two physicists —the one belonging to the experimentalists, the other to the theoreticians—is by no means the least of the reasons why it is so well balanced an account of how the new knowledge has been achieved, and of how it has been successfully brought within the framework of ever-widening concepts. I believe, too, not only that each reader of this book will correctly perceive to how great an extent any advance has been based on a reciprocally fruitful linkage of research with technology, but also that he will have brought home to him very strongly the fact that such a far-reaching development as this in one part of the scientific field has been made possible only by the most intimate co-operation between scientists from, so to speak, all parts of the scientific world. The modest contribution made by the individual to this co-operative work finds its value only in being fitted into that structure whose deepest foundation in the end is the abiding impulse in every human being to seek order and harmony behind the manifold and the changing in the existing world.

PROFESSOR NIELS BOHR

Authors' Foreword

Of late years there seems to be a strongly growing interest in research on the atom, and it has seemed to us that an account giving a summary of this subject, treated so as to be understood without any excessive demands on the reader, would go to meet a widespread demand from a public interested in science.

We have decided to describe the development of modern atomic physics from its first beginnings at the end of last century down to our own day. This mainly chronological account of its development will give the most instructive impression of our present-day achievements. Naturally, atomic physics cannot be sundered without more ado from the rest of physics, for the two are organically bound together. We have therefore given quite a short explanation of those general physical and chemical concepts which are essential to the subject. This is done partly at those places in the text where the understanding of the passage calls for it and partly in the Introduction. This last also contains a short discussion on the development of the concept of the atom up to the beginnings of modern atomic physics.

The book falls naturally into three main divisions. The first starts with the great discoveries about the beginning of our century, which were the foundation of further developments, and ends with Rutherford's discovery of the atomic nucleus in 1911. The next division treats of the whole atomic theory from its revolutionary beginnings in 1913, with Bohr's theory, down to its last stage about 1926, the working out of quantum mechanics. It is possible that this division contains some things not easily understandable at a first reading, but it will hardly be possible further to simplify the statement of these difficult theoretical questions without distorting

the picture of the smallest particles of matter given us by the atomic theory.

On the other hand, the last and longest division of the book, that dealing with the epoch-making experimental discoveries of the last few years in respect of the atomic nuclei, will be very easy to read, and its understanding will not demand a grasp of all the details given in the theoretical division. This last division is continued right up to 1938. We have, however, taken into account among the latest discoveries and advances only those whose truth may be considered as being beyond all doubt.

To lighten the reader's task, all those technical details which are not absolutely necessary to the understanding of atomic structure are printed in italics, while formulae and the like, which make greater demands on the reader, are given in footnotes. We have appended at the end of the book a list of all the manifold particles that play a part in the atomic world in order to make a general understanding of them easier. It is advisable to refer to this while reading.

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Introduction

ONCE we have left childhood behind and have long absorbed the mysteries of the alphabet, we generally give no further thought to the fact that any book, no matter what its contents, contains no more than a score or so of different letters. But it is amazing that with only these few signs we are able to build up the many thousands of words which make a language.

It is equally wonderful that all the many hundred thousand different kinds of matter that man has found in this world, when examined more closely, have turned out to consist of no more than ninety substances—the elements, as they are called. While a child can easily see for itself that each word in a book is composed of a selection from the letters in the alphabet, the task by which the chemist was faced in his study of Nature's book was certainly more difficult.

The reason is, that it is impossible to see which are the elements any given kind of matter contains, for the properties of a composite matter are always quite different from those of the elements of which it consists. Thus it is wholly impossible to see from matter such as water that its components are the two gaseous elements oxygen and hydrogen, whose properties are very different from those of water. Only far-reaching analyses by chemical methods gave us our present division of all matter on the earth into the two main groups: *chemical compounds and elements.*

Man had been speculating on the nature of matter for hundreds of years before chemistry helped him to this knowledge of how the various kinds of matter are built up. He had found it quite probable that each kind of matter was built up from its own absolutely identical particles, which could not be further split up. For these particles the old

Greek philosophers used the name *atoms*, which means *the indivisible.*

When the fundamental discoveries in chemistry were made about 1800, the conception of the atom at once assumed great importance. From being no more than a pleasing idea it came to be a useful one, which could be employed as a working hypothesis. The atomic theories now assumed more closely defined forms, a distinction being made between the smallest particles of the chemical compounds, which were given the name of *molecules*, and the smallest particles of the elements, for which the name *atoms* was reserved. Since a chemical compound always shows exactly the same properties, however small the quantity which is investigated, even the smallest parts of a chemical compound must contain all those elements that make up the compound, so that the compound's molecules must be made of a determinate number of atoms of each one of these elements. Thus, while there are no more than about ninety different kinds of atoms—that is to say, exactly as many as there are elements—there must be many hundreds of thousands of different kinds of molecules, corresponding to the number of different chemical compounds.

This working hypothesis yielded natural explanation for the fundamental fact that on analysing any given chemical compound we always find that it contains its elements in exactly determined proportions by weight. This is at once understood when it is also assumed that the atoms of any given element have all exactly the same weight, which, however, differs for different elements. The determination of the proportions of the weight of the different elements in every possible chemical compound thus gave chemists a means of finding the relation between the weights of the different atoms, and also of determining the precise number of atoms making up the molecules of a given compound. By the use of such methods it was established, for example, that

a molecule of water is made up of two atoms of hydrogen and one of oxygen, and also that the weight of the oxygen atom must be sixteen times as great as that of the hydrogen atom.

On the other hand, the real weight and size of atoms or molecules cannot be determined by the methods of chemistry. But it is quite clear that these atoms and molecules must be immeasurably small, since even the most powerful microscope does not show the slightest indication of any such atomic structure of matter. With the help of the microscope we can pick out distances down to a little under one-thousandth of a millimetre, so that the diameter of atoms must be much less than this. Their number must therefore be enormous. Although the concept of the atom proved so useful in explaining the facts of chemistry, right down to the end of last century there were still many investigators who doubted in their heart of hearts whether the atoms existed at all, for it was hard to see how it could ever be possible to observe the working of individual atoms.

But the concept of the atom also helped us to win a deeper understanding of many purely physical phenomena, and especially of the well-known conceptions of heat and temperature. Even at a primitive stage of development men were aware that heat could be brought about through friction, and use was made of this knowledge to make fire by rubbing two pieces of wood violently against each other. Through chemistry investigators had now become more at home with the concept of the atom and they were led to the supposition that heat was in reality nothing else than movement of the atoms and molecules of the various kinds of matter, which could be brought about, for example, by rubbing rough surfaces together. This again was, of course, only a working hypothesis, since owing to the minuteness of the atoms and molecules there could be no direct observation of any such motion. But the hypothesis yielded a natural

explanation of so many everyday phenomena that it gave strong support to the atomic outlook on nature.

When we have to do with a solid substance, as for instance a piece of lead, it is to be assumed that the individual atoms lie very close together, and that strong forces are at work between them, holding them in position, so that the substance keeps its form. According to the hypothesis of heat as motion all the atoms would make small oscillations around their positions of equilibrium, the oscillations becoming quicker as the temperature rises. If, then, a piece of lead is heated to a sufficiently high temperature, the result may be that the oscillations become so powerful that the atoms break away from their positions of equilibrium and begin to wander around among themselves, a state of affairs revealed by the melting of the lead. It is always to be assumed, however, that the atoms are holding together to a certain degree in the molten lead, since it does remain in the crucible where it was melted. If still further heat is applied, the lead atoms will attain such a speed that the swiftest of them will break through the surface of the fluid, and then the molten lead evaporates. Such considerations leads us, therefore, to a natural explanation of the fact that the various kinds of matter can exist in the three several states: solid, liquid, and gaseous; the change in state being nothing else but a change in the distances separating the atoms or molecules.

These theories were soon developed to the point at which it was possible to make exact calculations for atomic motion, and further, to give a first determination of the number of atoms in a given amount of matter, and so of the approximate size and weight of atoms. Since we have to-day more direct methods for determining these quantities, and since in the following pages these methods will be the subject of more detailed discussion, the way in which progress was originally made has now only an historical interest, so that it will be enough if we give the results attained, Thus, it was

found that 1 gramme of hydrogen contains about 6×10^{23} atoms,* or, to express this in another way, 600,000 million million millions of atoms. Since these 6×10^{23} hydrogen atoms together weigh 1 gramme, one hydrogen atom must weigh $\frac{1}{6 \times 10^{23}}$ or $1 \cdot 6 \times 10^{-24}$ grammes. Now that we have the absolute weight for one kind of atom, it is easy to find the absolute atomic weight for any element, for we make use of the above-mentioned results reached by the chemists, giving the proportions between the atomic weights of the various elements. Since, for example, the atomic weight of oxygen is found to be sixteen times that of hydrogen, the atomic weight of iron fifty-six times that of hydrogen, and so on, we have only to multiply the weight of the hydrogen atom by these numbers to get the actual atomic weights of these kinds of matter.

Finally it was also found possible to give an approximate value for the size of atoms. It was found that this diameter must be about 10^{-8} centimetres, that is to say, a hundred millionth of one centimetre. These unbelievably small measurements for the size and weight of atoms, as also their fantastically great numbers, were not very helpful in convincing those who had doubts whether the atoms really existed, for it seemed more unlikely than ever that we should

* In atomic physics it is often necessary to give both very small quantities and very great numbers, and use is made of a most convenient notation, well known in mathematics, to avoid writing so many noughts. Large numbers, such as 1,000,000 or 1,000,000,000 are written respectively as 10^6 and 10^9, the small number above the line showing the number of noughts that is to follow the number one, or in other words, the number of times 10 is to be multiplied by itself to yield the number. For small fractions, such as $\frac{1}{1{,}000{,}000}$ or $\frac{1}{1{,}000{,}000{,}000}$, in like manner the symbols 10^{-6} and 10^{-9} are used. Finally a like notation is used when some other number is to be multiplied by itself several times. For instance, 2^5 (which is read as "two to the fifth power") has the same meaning as $2 \times 2 \times 2 \times 2 \times 2$ ($= 32$).

succeed in observing the working of the separate atoms. On the other hand, the followers of the atomic theory held the view that the end of the road which leads to the understanding of nature might be said to have been reached, for it was believed that we had come down to the smallest particles that go to build up matter.

It was here that modern atomic physics entered the field. New discoveries, while yielding the definitive proofs of the existence of the atoms, also showed that they were not indivisible, as it had until then been assumed, but that under certain conditions they could be split up into still smaller particles, showing quite new and surprising properties. Although the word "atom" originally meant "the indivisible," the term has been retained for the smallest quantity of an element that is still in possession of all the physical and chemical properties of this element.

This book will now give an account of this modern atomic physics, which seeks to explain how the atom is built up from still smaller particles, and how it is split up into them.

I

The Golden Age of the Great Discoveries

MODERN atomic physics may be said to date from the end of last century, at a time when all physicists were more or less at one in believing that all the great discoveries had long ago been made. They had made the laws both of mechanics and of electricity and magnetism their own, and these seemed to form a closed system, which left no room for further knowledge. The general point of view was that physics had been brought to its full fruition and could now do no more than give the foundations for technology.

But what actually happened was that one remarkable discovery followed the other. The world was thrown into utter astonishment. These discoveries were quite at variance with that smoothly rounded picture of the world which had been reached by natural science in earlier centuries. The discoveries of radium, of electrons and of the Roentgen rays not only shook natural science to its foundations, but they also aroused the greatest interest outside the narrow ring of the physicists.

RADIUM

It was probably the discovery of the radio-active forms of matter with their mysterious rays that above all fastened attention on this field. The beginning was made in 1895 when Becquerel in France noticed that it was not advisable to keep photographic plates in the neighbourhood of certain minerals, since these latter sent out invisible rays which blackened the plates right through their packing, as though they had been exposed to the light. A more careful search for the source of these penetrating rays showed that several

of the heaviest elements had the remarkable power of sending forth these rays continuously and without any action from outside. These rays, besides their penetrating and their photographic action, had the no less extraordinary property of being able to change the air from a non-conductor to a conductor of electricity. It was now possible with delicate electrical measuring instruments to measure the conductivity of air brought about by a radiation of this kind, and thus a means was found for a profounder investigation of the properties of the rays, and also a means of searching for other radio-active kinds of matter.

Using such methods as these, Pierre and Marie Curie—husband and wife—succeeded in 1898 in finding the most powerful and best known of these elements, namely *radium*, whose radiation was so strong that biological effects could be observed. It is especially its action on living tissues that has made radium the wonder-matter for the popular mind. In the fight against cancer and other illnesses the doctors found in radium a curative instrument whose effects seemed like witchcraft, for the bare application of this matter to the afflicted place was able to bring about the disappearance of the disease. But the rays might also be dangerous, since a few grammes of the matter could have deadly results if anyone were exposed unprotected to its radiation for any length of time. Not a few scientists and medical men lost their lives, before it was found out how protection could be given against the rays.

We can readily understand that such discoveries as these quickly led to far-reaching researches into the properties of the rays. It was very soon learned that there were three different kinds of rays: α-rays, β-rays and γ-rays,* which differed from one another through their differing powers of penetration and of making the air a conductor for electricity.

* α = Alpha, β = Beta, and γ = Gamma are the three first letters in the Greek alphabet.

The α-rays had very peculiar properties, without parallel in the history of physics. Their property of making air conductive and blackening photographic plates was very pronounced and besides this they could cause serious burning of the skin unless care were taken. But it is easy to protect oneself against the α-rays, for all effects are lost a few centimetres away from the given substance. In fact, the α-rays have a sharply defined range of action in the air, which varies only a little for the different α-radiating substances.

A decisive step was made in the search as to the nature of the α-rays with the discovery that they could be affected by a magnet. They were not attracted by the magnet, as a piece of iron is attracted, but on the contrary were deflected at an angle to the direction of the magnetic flux. An effect like this from a magnet is a well-known phenomena in physics: a wire through which an electric current is passing is acted on through a magnet by a force at right angles to the direction which would be taken by a piece of iron. This force, known as electro-magnetic force, is made use of in electro-motors, since, with its particular direction, it can easily be employed to produce a rotation. As the α-rays are deflected by the magnet in exactly the same direction as is a conductor carrying a current of positive electricity, it is a natural presumption that the α-rays are made up of a stream of particles charged with positive electricity, these particles being known as *α-particles*. Later on we shall go into the question of how the pursuit of the experiments on the deflection of the α-rays by a magnet bore out this presumption. It was found quite possible to measure the speed, electric charge and weight of the α-particles (page 41).

To examine the properties of the β-rays by themselves it is enough to put the preparation of radium into a glass tube, for the α-particles are all stopped by the glass wall, while the β-rays go through it pretty well without hindrance. For these β-rays have considerably stronger penetrating powers

than the α-rays and can cover several metres in the air. While passing through the air they make it a conductor for electricity, although in a less degree than do the α-particles. The β-rays are deflected with the utmost ease by a magnet, but in the opposite direction to the α-rays, that is to say, in the same direction as a stream of *negative* electricity would be deflected. Therefore we assume that the β-rays are made up of a stream of negatively charged particles—the *β-particles* —which are thrown forth from the radio-active substance.

If our preparation of radium is wrapped in a metal case some millimetres thick, the β-particles are also wholly stopped, and we are left with only the *γ-radiation*. This is so very highly penetrating that it is not appreciably weakened by the air, and a certain percentage of the radiation is still left even after passing through a lead plate 8 cm. thick. It is the γ-radiation that is used in medicine, since its penetrative power enables it to give a uniform irradiation for even deep-seated tumours. On the other hand, γ-radiation for the same reason is also the hardest from which to find protection. If we try once more to make the experiment of deflection by means of a magnet, we find that the γ-radiation is not in the slightest degree deflected, so that it may be concluded that these rays, as opposed to the α-rays and the β-rays, do not carry any electric charge. They must therefore be of an altogether different kind.

This knowledge of the characteristic properties of the rays emitted by the radio-active substances was, however, not enough to solve the great riddle of their emission. It was a series of important investigations by Rutherford and his pupils that led, in the first place, to a deeper insight into the phenomena characteristic of the radio-active substances. First and foremost, it was found that the radio-activity of a given element was wholly independent of whether or not the element was in chemical combination with other elements; this was something quite new, seeing that in other

respects chemical compounds are known to have quite other properties than those of their constituent elements making them up. Further, experiments were made with a view to ascertaining whether it was possible in any way to influence the emission of rays by the radio-active substances: for example, by heating or cooling the substances by other physical or chemical action. In the result the radio-activity showed itself to be wholly unaffected by any form of action from without. An even more important result was that by careful measurements in the case of various substances it was shown that the strength of the radiation was not constant, but that it diminished with time, which could be taken to mean that the quantity of the radio-active matter decreased in proportion as it emitted its radiation.

To explain these remarkable facts Rutherford in 1902 put forward what at that time was the extraordinarily bold hypothesis, that in radio-activity we have really a *transmutation of elements,* which occurs of itself, without any need of experimental interference, and quite independently of any chemical combination in which the element in question may be held. According to this hypothesis, the strength of the radiation at any given time should be exactly proportional to the amount of the matter then present, so that the radiation would fall to one-half when half the matter had been transformed. By means of most ingenious and careful micro-chemical observations, together with continued observations of the intensity of the radiation, the nature of these radio-active transformations was fully elucidated by a few years' research, and it was found that Rutherford's working hypothesis was confirmed in all its details so that it could be accepted as actual fact.

In order that we may have a rather more exact conception of what happens in the radio-active transformations, we will imagine that £10,000 is placed at our disposal for the purchase of one gramme of radium. The radium is delivered,

freshly purified, in a small sealed glass tube, which is enclosed in a protective capsule of platinum. If we immediately set to work to examine the radiation emitted, we reach the discouraging conclusion that the preparation is not emitting any rays at all. The explanation of this result is that pure radium emits only α-rays, and these have not the power of penetrating the glass tube, let alone the platinum capsule. We now wait patiently for two or three days, and we then find that the preparation is gradually beginning to emit a penetrative γ-radiation, which grows stronger day by day, until by the end of about one month it has reached its full strength, which thenceforth it would seem to maintain unchanged. If we were to remove the platinum capsule we should find that a β-radiation was on its way. What has happened while we have been waiting is that a small fraction of the radium has been transformed into other radio-active elements. For while the radium is sending out α-particles, the metallic element radium is being transformed into another element, which is gaseous, and is known as *radium emanation*. This gas, however, is itself radio-active; like the metal, it emits α-particles, and in so doing it is transformed into a new radio-active substance, which is a solid, and is known as *radium A*.

If we carefully cut a hole in the little glass tube, we can pump the gaseous emanation into a container, and so examine its properties separately. We shall then find that, as we have said, it sends out α-rays, but that the radiation decreases so rapidly that after the lapse of barely four days it has only half its original strength. At the same time, one-half of the emanation has disappeared, which we can prove by measuring its volume, the vanished gas having been transformed into the solid substance radium A, which takes up hardly any room. In the same way each radio-active substance has its specific and determined rate of transformation, which can be expressed in terms of the *half-value period*:

that is to say, the time which elapses before one-half of the substance has been transformed, and the strength of the radiation sunk to one-half. While radium itself has a half-value period of 1,600 years, and the half-value period of the emanation, as we said, is about four days (96 hours), radium A is halved in only three minutes, being transformed into *radium B*, which again is halved in 27 minutes, *radium C* being formed; and so the process continues.

But we must not think that in this way we can go through

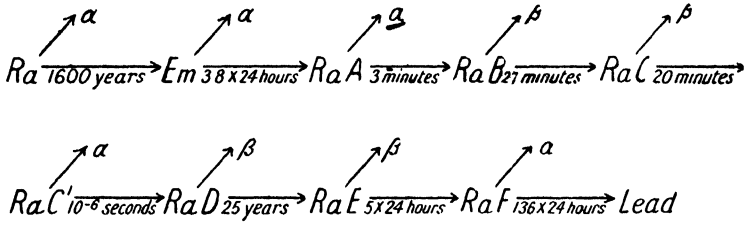


FIG. 1

the whole alphabet. The transformations continue only a few steps further, so that a whole radio-active family, as it is called, is founded, whose family tree can be set out as shown in Fig. 1, where the abbreviations Ra and Em stand for *radium* and *emanation*. We see from this that the different steps or generations have each their characteristic half-value period and ray, and that at last the transformations come to an end, the final member of the family being nothing more or less than ordinary lead, which, as we know, is not radio-active.

We assumed above that we opened the glass tube and pumped the emanation out. If, on the other hand, we let the emanation remain in the closed glass tube together with the radium, the radio-active transformations continue unhindered. The only thing now is that as the radium is transformed there will be a steady supply of fresh emanation,

to take the place of that emanation which is disappearing during the transformation. Thus there will occur a state of equilibrium in which at every moment there is transformed exactly as much emanation into radium A as emanation is newly formed from radium. The same holds true for the other substances, so that every single member, when the family has in due time reached its full numbers, will be found existing in a fully determined quantity, a quantity depending on the rate at which the formation from the mother-substance proceeds, and how speedily this latter is itself transformed into a daughter-substance. Our gramme of radium, so pure at the beginning, has thus been contaminated from within itself by very small quantities of these dozen or so new radio-active substances, and has by this very fact reached its full radiating strength.

The many details that are expressed in the genealogy of the radium family, and in the corresponding genealogies of the two other radio-active families that have been discovered —the thorium and the actinium families—must not, however, lead us to forget the main thing: namely, the fact that radio-activity has shown itself to be linked with something so revolutionary as a transformation of elements, by which not only the conception of the element but also the hitherto accepted conception of the atom has become unsettled. For a *transformation of the elements* must, as a result of the definition of the atom, be *the same thing as a transformation of the atom.* We have therefore to believe that a radio-active transformation consists in the emission from the individual atoms of sub-atomic constituents: that is to say, of particles smaller even than the atoms, in the form of α- or β-particles; and after this has happened the remaining constituents in the atom give rise to the atom of the new element. Thus, each time we observe an α- or a β-particle we have tidings that there has been a transmutation of one element-atom into another. On the other hand, the emission of γ-rays, which

does not involve any electrical charge, is merely a phenomenon accompanying α- and β-emission, which in itself has no significance in respect of radio-active transmutation; and for this reason the γ-rays are not given in the genealogy of the radium family.

The half-value periods given for the various members of the radium family are not all based on direct measurement of the speed at which the radiation lessens; in particular, this is naturally true of radium's half-value period (1,600 years), for this substance has been known for only about forty years. There is, however, another way of determining the half-value period. Among the substances in a radio-active family which has reached the state of equilibrium there will always be more of those substances which have a long half-value period, while substances with a short half-value period will be found only in small quantities. Closer reflection shows that the number of atoms present of the various substances must be exactly proportional to the half-value period of the substances, so that by measuring the quantities of matter in the state of equilibrium we can determine some of the half-value periods, if other of these periods are known to us.

Radio-activity is the first example in the history of physics to show that it is within the range of possibility to study *individual* atomic processes, and thus the main objection (referred to in the Introduction) against the atomic theory of matter falls to the ground. The radio-active substances, moreover, may well throw a valuable light on the structure of atoms, since quite of themselves they provide us with separate fragments of the atoms for us to examine at our convenience, just as a volcano yields the geologist materials for investigating the depths of the earth.

It will not, perhaps, be out of place to refer here and now to one or two important instruments used by the experimental physicists in studying radio-active transformations. One of these has the advantage that nearly anyone can find an opportunity of making use of it, and so being convinced

by his own observation of the reality of atomic processes. We are referring to the self-luminous wrist-watches or alarm-clocks familiar to all, whose figures or hands are coated with a very thin layer of radium salt mixed with a substance, *zinc sulphide*, which has the property of emitting small flashes when it is struck by an α-particle. If we watch one of these self-luminous watch-figures through a small magnifying glass, especially in a perfectly dark room, we shall witness the most splendid firework display in the shape of small green flashes, continually kindled and extinguished, here, there, and everywhere, each flash showing that an α-particle has been emitted, so that we get a vivid impression of the fact that the α-rays are made up of separate particles.

This experiment is more than a mere curiosity, for exactly the same method has been extensively used for elucidating radio-active phenomena by direct counting. This method of observation consists in making the α-particles strike a small screen coated with zinc sulphide and watching it through a microscope. Such counts, which involve a very heavy strain on the observer, can be carried out only in a perfectly dark room and after the eye has become used to the dark, and then only if the frequency of the α-particles is not more than about thirty to the minute.

By counting the α-particles which in a given time strike a screen of a given size, at a given distance from a known weight of radium, we can work out the total number of α-particles shot out in each second by the preparation in all directions. By such counting it has been ascertained that 1 gramme of radium sends out altogether $3{\cdot}4 \times 10^{10}$ α-particles to the second, which is the same thing as saying that in one second this same number of radium atoms is transmuted. Since now, thanks to the half-value period, we know the rate at which radium atoms are transformed, and thus what fraction of the whole quantity of radium is transformed in each second, we can reckon the whole number

of radium atoms in 1 gramme of radium. This number is found to be $2 \cdot 7 \times 10^{21}$ radium atoms for 1 gramme. We can now also calculate how many atoms there are in 1 gramme of any element we choose by making use of our knowledge of the relations between the atomic weights of the elements. Since radium's atomic weight is 226 times that of hydrogen, there must be in 1 gramme of hydrogen 226 times as many atoms as in 1 gramme of radium, that is to say, 6×10^{23} hydrogen atoms in a gramme, which yields a confirmation of the number given in the Introduction, and so also of the weight given for the atom of hydrogen. This method of determining the number and absolute weight of the atoms is one of the most direct methods at our disposal. That this method leads to the same value for the weight of the hydrogen atom as other wholly different methods is a striking proof of the truth both of our conception of the atom and of Rutherford's hypothesis as to the transformation of the element in radio-activity.

We have a still more beautiful, but at the same time a difficult method for bringing before our eyes the emission of separate parts of the atom during radio-active processes, in what is known as the *cloud-chamber*, in which, by means of a special artifice, we can make α- or β-particles draw their own paths as streaks of fog, much as a smoke-writer in the sky draws his own path, even if he be so high up that he himself cannot be discerned. Later on we shall deal with the construction of the cloud-chamber and its working; here we will do no more than show one or two photographs of these paths. Fig. 2, Plate I, page 41, shows α-ray tracks from a thorium preparation containing a mixture of two α-radiating substances, so that two sets of α-particles are seen, each with its defined range. In Fig. 3, Plate I, page 41, we see a remarkably fine picture of α-particles from the same substance, only in a stronger preparation. These pictures show clearly enough that the α-rays are made up of indi-

vidual particles proceeding in a straight line from the radio-active matter.

Now that we have learnt from the radio-active phenomena that *atoms must be composite*, since *atoms can be split up*, when they send out electrically charged parts, we will for the time being pass on from radio-activity to other departments of physics, which have also given us a first inkling of the structure of atoms.

THE DISCOVERY OF THE ELECTRONS

Every radio amateur knows to-day that glowing substances send out *electrons*, and that these are remarkably willing little entities, which in a radio receiver can be made to swing in time with the notes of a jazz orchestra, or to draw moving pictures at lightning speed on the screen of the television receiver. But these swift little entities of the sub-atomic class have not always been known to us: they had first to be discovered, and this was, as a matter of fact, one of the greatest and hardest-won discoveries ever made in physics. Owing to these very difficulties the discovery of the electrons cannot be attributed to any one man, but has come about as a result of prolonged investigations, both theoretical and experimental, carried on by many research-workers.

There had long been speculations as to the nature of electricity, and such questions had been raised as, for instance, how far a body charged with electricity becomes heavier, or what happens when an electric current is passing through a copper wire. In spite of the most careful measurements, however, no one had ever succeeded in demonstrating any rise in weight when a body was charged with electricity.

Any answer to questions such as these was made difficult by the fact that, so far as could be seen, electricity was always bound up with gross matter. It was therefore a discovery of the highest importance when by the use of special devices an electric current was successfully made to break away from

matter and continue to flow through empty space This successful attempt had already been made about the middle of the last century, and the method was to try, with the help of a high electrical tension, to send a current through an almost evacuated glass container into which had been fused conducting wires, *electrodes*, for introducing the current, as shown in the sketch in Fig 4 It was then found that from the negative electrode, the *cathode*, there proceeded a rectilineal radiation which was in itself invisible, but whose

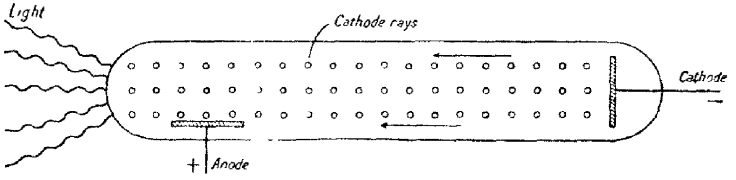


FIG 4

existence could be shown by the fact that it gave rise to a bright spot where it struck the glass wall or other solid substances Later it was found that the rays known as *cathode rays* could be deflected either by a magnet or by electrically charged bodies, and in such a direction that the only conclusion possible was that a current of negative electricity was present

These properties of the cathode rays could now be explained without any difficulty, if it was assumed that they consisted of rapidly travelling, prodigiously light, and identically similar particles, all possessing the same negative electrical charge For such particles must be shot from the cathode into the rarefied air of the tube at a speed corresponding to the electric potential to which the cathode is charged, just like small projectiles which are fired at so short a range that their trajectory becomes a straight line

We shall now try to advance a few simple considerations as to how such electrical particles will be affected by electric

and magnetic forces. If a negatively charged particle passes close by a positively charged plate, it will be attracted with a force whose strength will be in proportion to the electrical charge of the particle. The measure of the deflection from the straight line will depend not only on the deflecting force, but also on how heavy the particle is, and at what rate it is moving. A heavy particle with a high speed is harder to deflect from its path than a light one moving slowly, as most of us must have noticed in all sorts of ball games. Precisely similar considerations can be advanced as regards the deflection of the particle by a magnet of a given strength; and from this we can see that if we measure the amount of the deviations in these two different deflection methods, we shall be able to obtain some knowledge of the charge, mass* and speed of the particles. But we have to acknowledge that from the two "equations" we cannot find all three "unknowns," but, as closer consideration shows, only the velocity of the particles and the relation between their charge and mass.

If we make such an experiment with electric and magnetic deflections of the cathode rays, we shall always find a sharply-defined spot on which the rays strike, which shows that all the particles have suffered the same deflection, and must therefore be identically similar. By means of such experiments, which we owe especially to J. J. Thomson of England, the velocity of the rays was now successfully calculated, and it was found to be greater in proportion as the electric potential applied to the tube traversed by the cathode ray was higher. The velocities found are as a rule somewhere about 100,000 kilometres a second. On the other hand, one unvarying value was always found for the relation between the

* In physics the concept *mass* is used instead of *weight*, when we wish to express a body's resistance to changes in motion. But since this resistance is proportional to the body's weight, the mass is expressed in the same units as the weight; that is to say, in grammes.

charge and the mass of the particles, which is a strong argument for the truth of the above views as to the nature of the cathode rays. If only we could now succeed in measuring the charge of the particles by means of some special experiment, we should, at the same time, automatically obtain the value for their mass.

Since the cathode rays are, so to speak, electricity in pure culture, we may indeed assume, from the experiments which we have described, that electricity consists of infinitesimal particles, a kind of electrical atoms, so that any given amount of electricity is made up of a great number of these particles, to which the name *electrons* has been given. For this assumption, which was at the core of a series of theoretical considerations known to physicists as the *electron theory*, proof was adduced by means of a great experiment in which Millikan of America succeeded in directly measuring the quantity of electricity pertaining to an individual electron. Millikan sat at a microscope and peered at some tiny drops of oil, which were so light that they could barely fall, and only sank quite slowly through the air. After contriving that the oil-drops should be charged with electricity he observed that their fall could be retarded or accelerated accordingly as a negatively-charged metal sheet was placed under or over the drops, which showed that the drops possessed a negative charge. By means of the microscope he now measured this change in speed for a great number of drops, and by so doing he was able to reckon the amount of electricity which the drops had taken up. It was found that this amount was not always the same, but it was, on the other hand, always an integral number of times more than the smallest quantity encountered. This smallest quantity of electricity, known as the *elementary electric charge*, must be identical with the electron's charge, for we have to conceive of the different oil-drops as having simply taken up one or more electrons.

With this achievement the discovery of the electron may

be said to have been completed, since its charge was known, and now its mass could be ascertained, as we have seen, by means of the cathode ray experiment. For this mass the value 9×10^{-28} gms. was found; but as this number will hardly arouse any very definite idea in the reader, we shall try to give him some notion, by a simple example, of how light electrons really are. Even were we to charge a copper ball one metre in diameter with a potential of one million volts—which we can just reach with a modern high-tension plant (see Fig. 33, Plate VI, page 129), and for which about a hundred million million electrons are required—the weight of the ball will be raised only by about one-millionth of one-millionth of one gramme. So that it is not so very wonderful that the attempt to find the weight of electricity by direct measurements should have been unsuccessful. For the physicist this number is not so imposing, since owing to the earlier determinations of atomic weights he was at home with small numbers; but what was interesting was the fact that the electron was seen to be about 1840 times lighter than the lightest atom—that is, the hydrogen atom.

It could therefore be suggested that in the electron we had found one of the stones which go to build up the atoms. This suggestion found further support in the fact that the β-particles known to us from their emission by the radio-active substances, when careful deflection experiments were carried out on them, showed the very same relation between charge and mass as the cathode rays, so that they could without more ado be assumed to be electrons. The only strange thing was that the β-particles had far greater velocities than the cathode rays, velocities for certain substances being found that were very near the velocity of light—300,000 kilometres a second. From Fig. 5, Plate I, page 41, which is a photograph of the paths of β-particles in the cloud-chamber, it may clearly be seen that the β-rays consist of separate particles. The photograph has been taken in the neighbour-

hood of a powerful magnet, so as to deflect the straight paths into circular ones, from whose curvature we can reckon the velocity of the particles

Once a fair degree of certainty had been reached as to the existence of electrons, they were found nearly everywhere Thus Richardson in England showed that metal wires at white heat send forth quantities of free electrons, and this method is the basis of the highly developed electron technique of to-day, which through radio, sound film, television, and so on, has come to play so prominent a part in the life of modern mankind

IONS AND THE IONIZATION OF ATOMS

The discovery that the electrons were a constituent part of atoms at once raised new problems, such as the question as to the number of electrons in the atoms, their motions, and the like Since the atoms are electrically neutral, we have to assume that beside the electrons they also contain positive electrical constituents whose total charge must be exactly equal to the charge of the electrons If therefore we succeed by some means or other in isolating atoms that have lost one or more electrons, they will necessarily show themselves to be positively charged And this result has been actually reached by fitting the original cathode ray tube of rarefied air with a perforated discharge tube in the cathode, as shown in Fig 6 Then, besides the usual cathode rays, there will be observed a new radiation passing through the tube in the cathode, and continuing in the space behind it, where it can be shown on a photographic plate

These *canal rays*, as they are called, can be shown, by means of electric and magnetic deflection experiments, to consist, like the cathode rays, of electrically charged particles, which however, are *positive*, and whose deflection demands much stronger electric and magnetic forces than are required for the deflection of the cathode rays This is found to be due to

the fact that the particles of the canal rays are much heavier than those of the cathode rays, so that here we are evidently dealing with precisely those residual elements of the atom for which we were seeking and which are known as *ions*. It is found that the properties of the canal rays besides being conditioned by the electric potential across the tube, are also in a high degree conditioned by the kind of gas which the tube contains, so that we may conclude that the canal rays are made up of ions formed by the atoms of the residue of gas remaining in the tube. By introducing various gases into

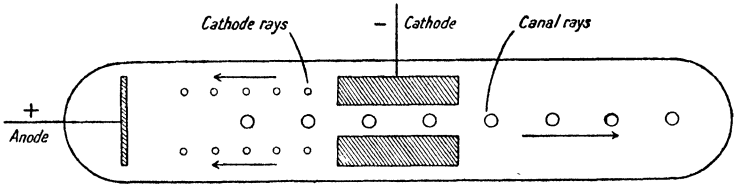


FIG. 6

the tube we are thus able to obtain canal rays or ions of the atoms of these gases.

Sometimes we find, for a given gas, two, or even three, deflection- or deviation-spots on the photographic plate, and these, on being measured, show that the ions in question must have made their appearance with either one or two or three positive elementary charges; in other words, that the atoms in question have lost one, two, or three electrons. Since the positive charge is now known, for it must be exactly the same in amount as the negative charge which went off with the electrons, we can, as with the cathode rays, by measuring the amount of the deviations or deflections, determine the weight of the ions, and thereby, since the mass of the electrons is infinitesimal, practically the weight of the atoms. If we make use of hydrogen as the other component with air in the tube, we once more find the weight of the hydrogen atom

to be $1 \cdot 6 \times 10^{-24}$ grammes, which is in perfect agreement with the value already given in the Introduction, and with the result reached when the counts were made of α-particles from the radio-active substances (cp. page 33). If mercury vapour is used instead of hydrogen, we find the mercury atom's weight to be about 200 times as great as that of the hydrogen atom, which fully agrees, again, with the proportion determined by the chemists between the atomic weights of these two substances. While by means of the original canal ray method, which we owe to J. J. Thomson, the atomic weights could be determined only for gaseous elements, the method has since then been more fully worked out, so as to become a precise means of determining the weights of all atoms (see page 120).

We can also perform, in respect of the α-particles from the radio-active substances, electric and magnetic deflection experiments of a similar nature to the canal ray experiments; it was through their magnetic deflections that these particles were found to be positively charged, like the ions in the canal ray tube. These experiments resulted in a complete explanation of the true nature of the α-particles, for they showed themselves to be identical with doubly charged helium ions; that is to say, helium atoms which have lost two electrons. Deflection experiments, it was found, gave exactly the same result for the relation between charge and mass as is obtained for doubly charged helium ions in deflection experiments with a canal ray tube which contains helium. The one and only difference is that the speed of the α-particles in the emission from the radio-active substances is far higher than that of the canal rays.

The evidence that positive ions are formed when the atoms lose one or more electrons affords the possibility of understanding what happens when gas is made conductive through radiation with, let us say, α- or β-rays. If two metal plates are set opposite one another with a certain thickness of gas

between them, while one is charged with positive, and the other with negative electricity, the plates being linked with a sensitive current-measuring instrument (galvanometer), this normally shows no current, for the gas between the plates is not conductive. If, on the other hand, the gas space between is irradiated with, let us say, α-rays, a current is set up in the galvanometer. The explanation is simply that the positive α-particles, while on their way, with the help of the electrical attraction which they exert on the electrons, pull some of these electrons away from the gas atoms, which then become ions, or, as we say, are *ionized*. The result is that we then obtain a mingling of neutral atoms, positive ions, and free-moving negative electrons. The two latter components will be set in motion through the attraction and repulsion exerted by the charged metal sheets, and so give rise to the electric current in the gas space between.

Thus we are now in a position to understand the construction of the cloud-chamber, whose operation is based on this same formation of ions. The construction of this cloud-chamber we owe to C. T. R. Wilson in England, who was a meteorologist, as well as a physicist, and so had twofold grounds for being well acquainted with the conditions under which mist is formed in the atmosphere. He knew that mist arises only when, in addition to a sufficiency of moisture in the air, there are also small bodies present, such as particles of coal-dust and the like, for the water-vapour to be condensed upon. But he now made the important discovery that water-vapour has also a tendency to condense around the positive ions to which the α-particles give rise along their path through the air, so that this path is seen as a streak of fog. The problem now was merely to introduce enough moisture into the air when it was wanted, and to get rid of the mist-streaks again when they had been examined. This problem was elegantly solved by Wilson by making his cloud-chamber in the form of a cylinder, within which a piston

PLATE I

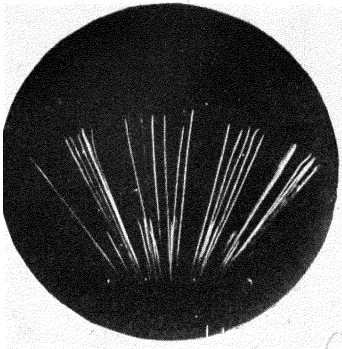


FIG. 2.—Cloud-chamber photograph of α-rays with two differing ranges.

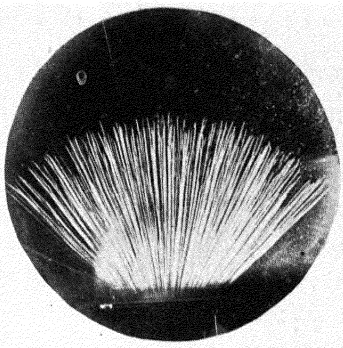


FIG. 3.—Cloud-chamber photograph of a strong α-ray preparation.

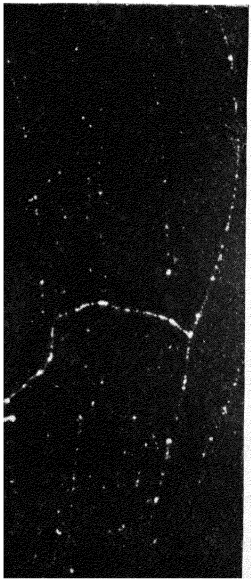


FIG. 5.—Cloud-chamber photograph of β-rays entering from below. The branching of one of the paths arises from a casual collision between the β-particle and an electron, which is thus set in motion and itself draws a path.

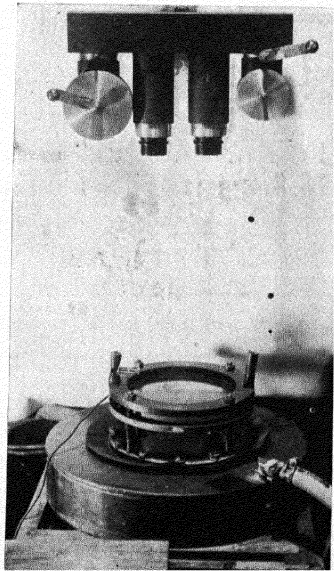


FIG. 7.—A modern cloud-chamber apparatus. Below is seen the cylinder-shaped cloud-chamber surrounded by a coil giving rise to the magnetic field for deflecting the particles. At the top is the photographic apparatus taking stereoscopic pictures of the paths, so that their spatial positions can be determined.

PLATE II

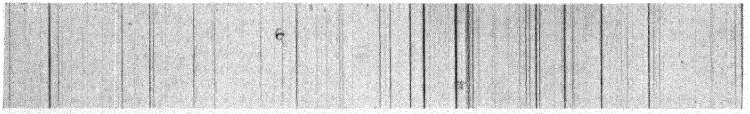


FIG. 9.—Photograph of the spectrum of iron between wave-lengths 3600A and 3800A.

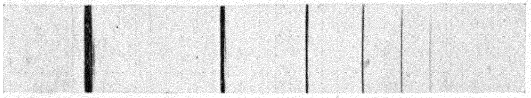


FIG. 10.—Photograph of the Balmer series in the ultra-violet part of the hydrogen spectrum.



FIG. 11.—Zeeman's phenomenon. At the top is seen the normal spectral line. Below, the splitting of the line under the influence of a powerful magnet.

FIG. 11

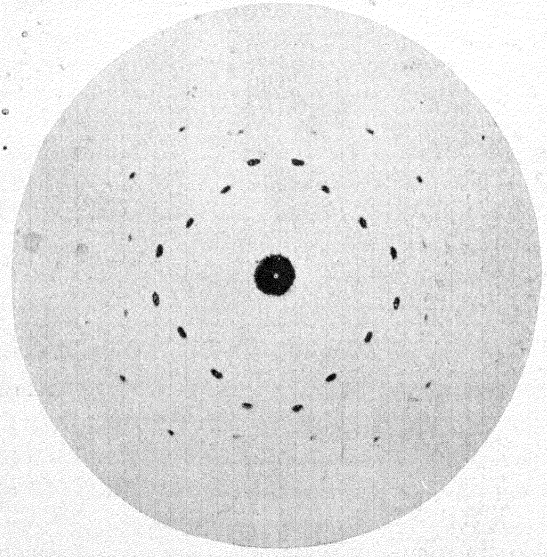


FIG. 13.—Interference of Roentgen rays on passing through a crystal of zinc-blende.

could be raised or depressed, so that the moist air could be rarified or compressed at will. When it is rarified suddenly air is cooled, so that its water-vapour content tends to form mist, as happens in the atmosphere when mist rises over a swamp after sunset. The cloud in the chamber, however, is formed only along the path of the α-particles, where there are ions enough, and by using a very strong light the paths can be photographed, showing as shining streaks on a dark background. If, again, the piston is made to compress the air, the latter is warmed, and the cloud streaks disappear like dew before the sun. In Fig. 7, Plate I, is seen a modern cloud-chamber.

From Fig. 5 we saw that the paths of the β-particles also could be photographed with the cloud-chamber; since these particles are able to ionize the air by knocking electrons away from the atoms. Since the β-particles have only half as great a charge as the α-particles, the electric force with which they act on the electrons in the atoms is only half as great. Moreover, the velocity of the β-particles is, as a rule, much higher than that of the α-particles, so that they need much less time to pass an atom, and therefore produce only short-lasting effects on its electrons. For these two reasons the β-rays ionize less actively than do the α-rays, which is shown by the fact that the paths of the β-particles in the cloud-chamber are much less dense than those of the α-particles, and all along the path we can make out the single drops of water, lying rather like beads on a string. From a cloud-chamber photograph we can thus easily decide whether we are dealing with the one or the other kind of particle (cp. Figs. 2 and 5).

We have now found that the atoms, when acted on from without, can be made to give off electrons, and thus to form positive ions. Here we will only remark that as a rule this is not a lasting change, for the positive ions that are formed, and the negative electrons that are set free, have by reason of their mutual attraction a great tendency to unite again as neutral atoms. In the ionizing of atoms we have, then, in

reality, an outside interference with the atoms, a kind of passing atomic decomposition, which the atoms themselves, after a shorter or longer period, overcome through the reunion of the fragments, Nature remedying the effects of the interference, much as when a lizard which has lost its tail grows it again.

RADIANT ATOMS

We now turn to what seems a widely different field of physical experimentation, known as *spectroscopy*; it includes the investigation of the light which substances can be made to emit, which has yielded valuable information as to atomic structure.

But we must first very briefly discuss what light really is. By many ingenious experiments and much correlated speculation, the knowledge was acquired in the last century that light consists of *electro-magnetic waves*, which spread out spherically from the luminous source in all directions, with a velocity of 300,000 kilometres a second, just as the waves on the surface of water spread outwards in circles when a stone is thrown into the water. In these days of radio most people understand what is meant by electro-magnetic waves and their *wave-length*; this latter is the distance between two consecutive maxima of the electric or magnetic force in the wave (see Fig. 8, page 47). In our radio programmes we find the wave-lengths of the electro-magnetic waves used by the European stations, and also a value, the *oscillation-number*, which gives the number of waves sent out in a second. The oscillation number is given in "hertz" or "kilohertz," 1 hertz being 1 oscillation a second.

If the wave-length of any station is multiplied by the oscillation-number the result is always the same, namely, the the velocity of the waves, which is, of course, always constant. For example, we take Stockholm, whose wave-length is 426 metres and its oscillation-number 704 kilohertz, and we

find that their product is approximately 300,000 kilometres a second, or Copenhagen, where 255 metres × 1,176 kilohertz gives almost exactly the same value. This is no accident, but is due to the fact that the wave-length of an electromagnetic wave is also the distance travelled by the wave during one complete oscillation. In one second the wave, then, will travel as many wave-lengths as are given by the oscillation-number, so that the velocity of the radiation must be equal to the product of the wave-length and the oscillation-number. A wave, therefore, can be identified, as we choose, either by its oscillation-number or by its wave-length, so long as we bear in mind that high oscillation-numbers correspond to small wave-lengths, and *vice-versâ*.

Just as the radio waves are due to the fact that the electricity in the transmitter's aerial oscillates back and forth many hundred thousands of times to the second (in the examples already given, 704,000 and 1,176,000 times), so the light-waves may be assumed to arise from oscillating electrical charges in the atoms. The wave-lengths, for the light rays, however, are less than one-thousandth of a millimetre, and so these charges must be assumed to oscillate with an oscillation-number of some hundreds of billions of times in a second. Since we have already been told that the atoms contain negatively-charged electrons, it is an obvious assumption that these electrons are at work in the emission of light. We see, therefore, that through the study of shining atoms we can obtain knowledge of the number of electrons in the atoms, and their motions.

Among the great discoveries made about the beginning of our century must be reckoned a set of experiments in the field of spectroscopy, where by careful measurements of the wave-lengths of the light which atoms can be made to emit, some remarkable regularities were discovered. The measurement of such small wave-lengths as that of light cannot of course be effected with an ordinary metre measure; it calls

for special methods, based on the characteristic property inherent in all waves—that of being able to set up *interference*; which means that two waves can either damp or reinforce each other. That is, if two trains of waves with the same wave-length are set going, as shown in Fig. 8, it may happen that the maxima of the waves coincide, in which case we have a reinforcement. But it can also happen that one set of waves is displaced in relation to the other by half a wave-length, in which case the maxima of the one train will coincide with the minima of the other, in such a way that the waves will weaken or damp one another, or wholly cancel one another out if they are equal in strength.

That unpleasant phenomenon affecting radio waves known as "fading out" arises out of this same interference between two radio trains of waves from the same station, when one wave goes up into the air and is reflected back again towards the earth, so that it runs into the wave which is taking a direct course. If we knew the length of this round-about course we could calculate the wave-length from it, since the delayed waves must have come half a wave-length or an odd number of half wave-lengths behind the direct waves if the result is to be a weakening of the waves.

Exactly the same principle is used in measuring the wave-lengths of light-waves: by means of highly-polished mirrors some of the light is made to follow an exactly known detour, so that interference occurs with the light that is taking the direct path. The detour, however, is so chosen that the difference between the paths is not one wave-length, but for instance 20,000 wave-lengths, and thus we obtain distances of about a centimetre, which can be directly measured with great precision. Through such measurements, which are among the most difficult known, Michelson in America has found the wave-length for the red light emitted by the element cadmium to be 0·00064384696 of a millimetre.

Where such small wave-lengths are in question as those of light, the unit of measurement generally employed is not the

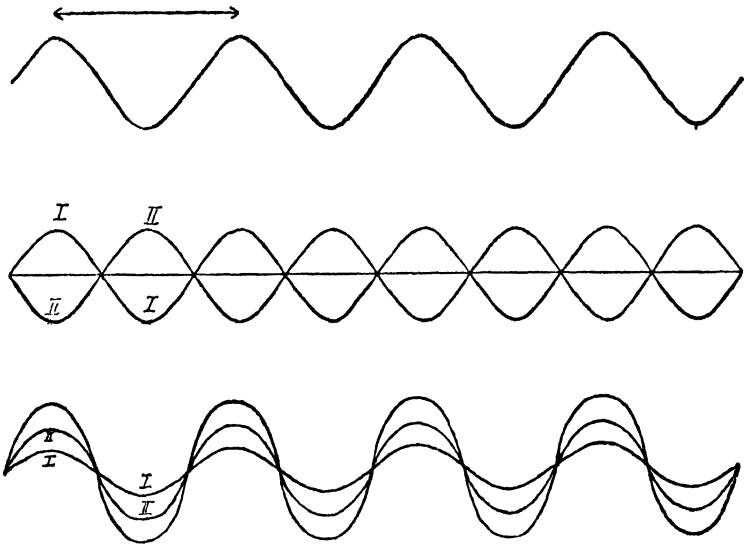


FIG. 8.—Schematic representation of waves and their interference. At the top is an instantaneous picture of the cross-section of, for example, a water wave, showing the wave-length.

Below this, interference between two waves I and II having the same wave-length, but displaced in relation to each other by half a wave-length or an odd number of half wave-lengths, so that wave-crests occur at the same time as wave troughs. As a result we have the horizontal line, that is, a smooth surface on the water, so that the two sets of waves wholly cancel one another.

At the bottom, interference between two waves I and II with the same wave-length but at different height and depth. The waves rise and fall in time with one another, that is to say, wave-crests coincide in time with wave-crests, and troughs with troughs, the result being a wave with the same length but of greater height and depth. The waves thus reinforce one another.

millimetre but the Ångström (Å), which is equal to 10^{-7} millimetres, and which takes its name from the Swedish

physicist Ångström, who carried out some of the first precise measurements of the wave-lengths of light. The red cadmium light has therefore the wave-length 6438·4696 Å.

In order to make the atoms emit light various methods are used, which all have this in common, that the element which is being dealt with is first of all reduced to the form of vapour, so that we obtain free atoms, and these can then be made to shine by means of electrical action. This is applied, for instance, by introducing a little of the substance into the arc of an arc-lamp, or by causing electric sparks to play between electrodes of the substance in question. For gaseous elements it is enough to enclose a little of the gas in a glass tube into which an electric current is introduced by means of electrodes fused into the glass; the tube, of course, must first of all be emptied of ordinary air. The well-known red and blue tubes of electric light employed for advertising purposes are a device of this kind, containing neon or mercury vapour.

Usually the light sent out from a radiant element contains many different wave-lengths; but these can be separated and examined with the help of what is known as a *spectroscope*, whose essential part is a three-sided glass prism. Such a prism has the property of deflecting light-rays out of their original direction, but in such a way that rays with differing wave-lengths are unevenly deflected. The light, after passing through the prism, will spread itself fanwise, and by means of a lens it can be made to form an elongated image in which the light of any given wave-length is seen lying in its own position. Such an image is called a *spectrum*, and now it is seen that every element has its fully-determined characteristic spectrum, in which the different wave-lengths are shown as clear-cut luminous lines, each of different colour, known as the lines of the spectrum, in which the order of the colours is precisely the same as that observed in the rainbow: that is, red, yellow, green, blue, and violet. The human eye is so made that it can distinguish between the light of differing wave-lengths, these being read by the retina and the brain

as different colours. Thus, the wave-length 0·0007 millimetres is read as *red*, 0·0005 mm. as *green*, and 0·0004 mm. as *violet* light. Lights with a longer wave-length than 0·00076 mm. or a shorter than 0·0004 mm., which are called respectively ultra-red and ultra-violet light, cannot be perceived by the human eye, but, on the other hand, can very easily be photographed.

By placing a photographic plate where the luminous image falls upon it we get a photograph of both the visible and the invisible parts of the spectrum. In such a photograph the spectral lines will not, of course, appear as coloured lines, but as sharp black lines whose position is determined by the wave-length. Fig. 9, Plate II, at page 43, shows a small part of the ultra-violet section of the spectrum of iron, which is especially remarkable for containing so many spectral lines.

In practice, if the wave-lengths of many spectral lines are to be measured in a spectrum, this is done, as a rule, by comparing the spectrum with another one, whose lines have been carefully measured beforehand, by interference methods of the same kind as were used by Michelson in determining the wave-length of the red cadmium line. To-day the wave-lengths are exactly known for most of the lines in the line-spectra of nearly all the elements, which means that we know the wave-lengths of several hundred thousand spectral lines.

The fact that each element has its specific spectrum is the basis of what is known as *spectrum analysis*, which is a method for discovering, by examining the spectrum of an unknown substance, what element or elements it contains. Spectrum analysis has played a very important part both in chemistry and in astronomy, for whether we are dealing with very small quantities of matter or with great quantities at vast distances, it has been possible to determine the composition not only of minerals but also of remote suns and nebulae.

But spectrum analysis has led also to the discovery of wholly new elements, since new spectral lines were found which had not been observed in the spectra of the hitherto known elements. In particular the discovery of the element *helium* by help of its spectrum is remarkable from the fact that the substance was discovered in the sun many years before it was found on the earth, which explains why it was named after the sun, whose Greek name is Helios.

Since the helium spectrum is marked by a particularly characteristic appearance, and can, moreover, be produced with very small quantities of helium, it was natural that the physicists should resort to spectrum analysis for a direct proof that α-particles are the same thing as helium ions. This proof was obtained in an extraordinarily elegant manner by Rutherford and his fellow-workers, who sent α-particles emitted by radium through an exceedingly thin glass wall into an evacuated discharge-tube, which then, after a certain lapse of time, showed the helium spectrum when a current was passed through it. The α-particles, therefore, must have matched electrons from the atoms in the glass wall, and in so doing they must have changed from helium ions to helium atoms.

Thus spectrum analysis is really no more than a practical application of the results of spectroscopy; but the physicists soon saw that the spectra were worthy of study in themselves. For in many of the spectra of the elements it was observed that the spectral lines were not distributed at random over the spectrum, but were arranged in a regular order by Nature herself. This was especially typical and striking in such spectra as contain what are known as *series*, by which we mean a set of spectral lines which, as they diminish in wave-length and intensity, come closer and closer together. This regularity was so conspicuous in certain spectra that the possibility was investigated of finding a simple numerical relation between the wave-lengths of the different lines in a

series of this kind. Balmer in Switzerland, in 1885, was the first to succeed in finding this relation for the lines in the hydrogen spectrum, which form a particularly evident series, of which we see a photograph in Fig. 10, Plate II, at page 43. He found that the oscillation-numbers of these lines could be expressed by the following simple formula:

$$\text{oscillation-number} = \frac{3{\cdot}3 \times 10^{15}}{2^2} - \frac{3{\cdot}3 \times 10^{15}}{n^2} *$$

From this we get the oscillation-number in hertz units by putting, in turn, $n = 3$, $n = 4$, $n = 5$, and so on. The corresponding wave-lengths are then found by dividing these oscillation-numbers into the velocity of light. How accurately this formula expressed the results of measuring the wave-lengths can be seen from the table here given, showing the observed and the calculated wave-lengths in Ångström units for the first eight terms in this *Balmer series*, as it is called.

$n =$	*Observed wave-length*	*Calculated wave-length*
3	6562·80 Å	6562·88 Å
4	4861·38 Å	4861·33 Å
5	4340·51 Å	4340·47 Å
6	4101·78 Å	4101·74 Å
7	3970·11 Å	3970·07 Å
8	3889·09 Å	3889·06 Å
9	3835·43 Å	3835·40 Å
10	3797·93 Å	3797·91 Å

This was a most remarkable result, not only because of the extraordinary accuracy with which this seemingly meaningless formula was able, in an almost miraculous way, to give wave-lengths which otherwise must have been laboriously measured, but above all because the wave-lengths were seen to stand in a mysterious relation to the series of whole

* The exact numerical constant was, however, $3{\cdot}28785 \times 10^{15}$.

numbers. Twenty-eight years went by before the veil was lifted from the mystery of the Balmer series, and we are able to obtain an insight into the mechanism of the emission of light from the atoms.

But the Balmer formula was far from expressing the only simple regularity found in the spectrum. As early as 1889 Rydberg, in Sweden, showed in a series of brilliant papers that the series in many other spectra of elements could be set forth in a like formula,* which was remarkable for containing exactly the same numerical constant as the Balmer formula, namely the constant $3 \cdot 3 \times 10^{15}$, which has therefore been given the name of the "Rydberg constant." This was a discovery of first-rate importance, since it might be taken to mean that there must be a certain uniformity in the architecture of the different atoms.

Furthermore, it is worth noting that the oscillation-number of the spectral lines according both to Balmer's and to Rydberg's formula is expressed as a difference between two quantities, and that this, at a later stage, was found to have a fundamental physical cause. These two remarkable achievements in spectrography are especially notable, among the vast number of other investigations in this field, as forming an essential part of the foundations on which the whole of the modern atomic theory rests.

We have still to speak of an important spectroscopic discovery which played a great part in forming our views on the emission of light by the atoms—the discovery by Zeeman in Holland, in 1896, of the action of a strong magnet on the spectral lines. Zeeman set his source of light between the

* Rydberg's formula was: oscillation-number $= \frac{3 \cdot 3 \times 10^{15}}{(m+a)^2} - \frac{3 \cdot 3 \times 10^{15}}{(n+b)^2}$, where m and n are whole numbers, while a and b are fractions that vary for the different elements, but are constant for any given series.

poles of a powerful electro-magnet, and then examined the spectrum in a very large spectroscope. He then found that some of the spectral lines were split up into three sharply separated lines, and that the distance between them increased in proportion to the strength of the magnetic field (see Fig. 11, Plate II, page 43).

This experiment was at once seized upon for theoretical treatment by Lorentz in Holland, who on quite simple grounds was able to show that just such a phenomenon was to be expected if it were assumed that the emission of light resulted from the oscillations of the electrons in the atoms. Such oscillating electrons, indeed, must be acted upon by a magnetic field in precisely the same way as the free electrons forming the cathode rays; and Lorentz's calculations showed that such action upon the atomic electrons will bring about such a change in their movements that in addition to the original light they must also emit light of a slightly greater and of a slightly smaller oscillation-number. This alteration in the oscillation-number must, however, depend not only on the strength of the magnet, but also on the electric charge and mass of the oscillating particles, for a heavy charge will, of course, be acted upon more strongly by the magnet than a light charge; conversely, a heavy particle will be less acted upon than a light particle, and will therefore yield a smaller variation in the oscillation-number. In other words, the change in the oscillation-number, and therefore in the wave-length under the action of the magnetic force, is a function of the relation between the charge and mass of the oscillating particles, just as in the case of the deflection of cathode rays by magnetic and electric forces. By measuring how far the spectral lines are split, and the strength of the magnetic field, we can therefore determine the relation between the electric charge and the mass of the oscillating particles. To the great triumph and delight of both Zeeman and Lorentz, and of physicists all the world over, the calcu-

lations showed the very same value for this relation as that already known for the cathode rays, so that it now could be taken as proved that it positively was the oscillation of electrons in the atom that gave rise to the emission of spectral lines.

Such research into the spectra of the elements was, however, for a long time, an isolated department of physics, and spectroscopists were regarded as being not far removed from cranks, whose work might be quite interesting, but was about as practical as crossword puzzles. Only after many years was it realized what immensely important material these cranks had obtained for laying the sure foundations that were to support the proud fabric of the atomic theory.

THE ROENTGEN RAYS

In the same year in which Zeeman and Lorentz made their great discovery, W. C. Roentgen in Germany was experimenting with a cathode-ray tube. There were, indeed, many others who were doing the same, but it was Roentgen who noticed that from the spot on the glass wall onto which the cathode rays fell thus proceeded, besides ordinary light, a wholly new kind of ray with most peculiar properties. These rays, which are now called after Roentgen, were especially remarkable in that they had the power of passing right through various opaque substances, the human body amongst others, though they penetrated light more easily than heavy substances. The rays themselves were not visible, but as they would affect a photographic plate, it was possible, for instance, to photograph shadows of the bones inside the body, since the bones are made up of denser matter than the rest of the tissues, and so are less penetrable by the rays. This purely physical discovery was very soon utilized by medical science, which found in it a most wonderful instrument for determining the locus and the extent of disease in

the organism. The methods of producing Roentgen rays were therefore very quickly developed and improved.

The most important advance consisted in causing the cathode rays to strike a heavy metal plate—called an *anti-cathode*—instead of the glass wall, and in employing a glowing metal wire to produce the electrons forming the cathode rays. In this it was found possible to produce Roentgen rays of great strength and penetrating power, which led to their further use in medicine, since these powerful rays appeared

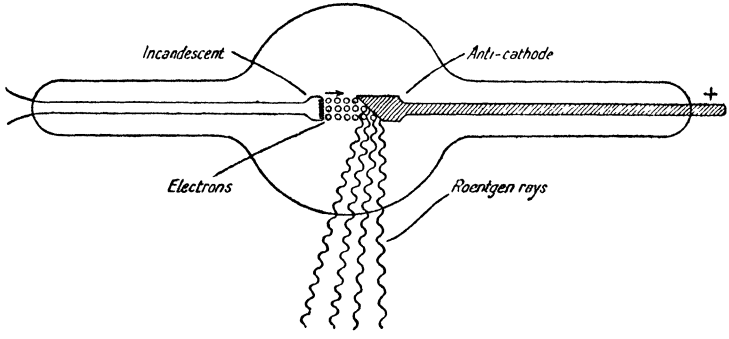


FIG. 12

to have a healing effect on cancers and other tumours; so that Roentgen ray treatment is in many cases an alternative to radium treatment. In Fig. 12, we have a sketch of the modern Roentgen or X-ray tube.

These important applications of the Roentgen rays were actually made before it was clear what the rays really were; but the physicists were not idle. Already Roentgen himself had shown that the rays could not, like cathode or canal rays, be deflected by electric or magnetic forces, and therefore the rays could not consist of electrically-charged particles. On the other hand, in their powers of penetration and their invisibility, and above all in the fact that they were not deflected by mirrors or prisms, the rays differed so greatly

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from light rays that it was hard to suppose that they could be electro-magnetic waves at all. At the same time various experiments seemed to show that the rays were actually rays of electro-magnetic waves, but waves of extremely short wave-length; though the definite proof of interference experiments was still lacking. As has been already said, in the measurement of wave-lengths in interference experiments it must be contrived that some of the radiation makes a known detour before it interferes with the rest of the radiation. If the rays have a very small wave-length the difference in the paths followed must be correspondingly small. Accordingly, if the Roentgen rays showed no interference phenomena when the usual methods were applied, this might be because the distances with which the experiments worked were too great.

In 1912 M. von Laue, in Germany, had the happy thought of using natural *crystals* as "mirrors" for the Roentgen rays. Owing to the tendency of these crystals to split in defined directions, it was generally assumed that the atoms lay arranged in regular planes, which lay at a very short distance apart; and it was this theory from which Laue started. For it was possible to hope that the Roentgen rays, being reflected from these planes, might be made to follow paths with a small enough divergence from one another to allow of interference phenomena. The idea was at once put into practice; a photographic plate was exposed close to a crystal, which was irradiated with a sharply delimited bundle of Roentgen rays. The plate then showed, as had been hoped, in addition to a heavily blacked spot on which the direct rays had fallen, a great number of blackened spots lying symmetrically distributed about the central spot, and corresponding to those directions in which the rays had reinforced one another by interference. Fig. 13, Plate II, page 43, shows one of these photographs, for which a zinc-blende crystal has been used, and where, in the many interference-spots, we have a direct proof of the wave-character of the Roentgen rays.

Since the distribution of the interference-spots can only be a function of the wave-lengths of the rays and of the grouping of the atoms in the crystal, it would be possible, by measuring the several distances between the spots, to calculate the wave-lengths, if we knew the distances between the planes of the atoms in the crystal employed. We can get some idea of how these distances can be calculated, if we reason as follows: since we know the absolute weights of the different atoms, as determined, for instance, by the canal rays method, it is a simple matter to calculate how many atoms are to be found in a crystal of known composition and of a given weight. Assuming that all the atoms lie evenly distributed throughout the crystal, we can also work out their average distance from one another. For a rock-salt crystal such a calculation gives a distance between the planes of the atoms of $2 \cdot 8$ Å, and when the distance between the atomic planes is known, it is easy to determine the wave-lengths of the Roentgen rays by means of interference experiments carried out with such a crystal.

The wave-lengths that have been found by this method lie between $\frac{1}{10}$ Å and a few Å, so that they are many thousand times shorter than the lengths of light-waves. Through Laue's experiment entirely new fields of physical research were opened up: on the one hand a whole technique of *Roentgen spectroscopy* was developed; and on the other, a profound study of crystal structures by the application of Roentgen rays of known wave-length. For we can just as well turn the problem about, and make use of interference experiments with Roentgen rays of a known wave-length to seek information as to the distribution of the atoms in unknown crystalline systems. Both these fields have to-day reached a high pitch of development, but since the latter is interesting mainly to mineralogists, we shall keep to Roentgen spectroscopy in the strict meaning.

A closer examination of the radiation emitted by a Roentgen tube soon showed that two kinds of radiation have to be

distinguished. The first kind is characterized by a spectrum containing all wave-lengths between determinate limits, and it is therefore known as the *continuous Roentgen spectrum.* Furthermore, this radiation does not depend on the metal employed for the anti-cathode and is conditioned only by the speed of the cathode rays; that is to say, by the electric potential applied to the Roentgen tube. This continuous Roentgen radiation is known also as *scattered radiation*, since it must be supposed to arise through the sudden braking and dispersal of the electrons by the anti-cathode. The basic laws of electricity and magnetism tell us that electro-magnetic radiation is emitted whenever charged particles alter their speed, and that the wave-length is shorter in proportion to this change of velocity. The emission of waves from an aerial, or from oscillating electrons in the atoms, depends wholly on the constant changes in the speed of the oscillating charges.

But besides this scattered radiation it was found, by the methods of Roentgen spectroscopy, that there is emitted also a wholly different kind of Roentgen ray, having only a few sharply delimited wave-lengths. This radiation is found to depend essentially on the material of the anti-cathode; so that it must be emitted from the elements contained in the anti-cathode. Thus, each element yields its fully defined *characteristic Roentgen spectrum*, consisting of rather a small number of spectral lines. These characteristic Roentgen spectra form, like the ordinary optical spectra of the elements, the basis of a spectrum analysis that can be put to practical uses, for the Roentgen spectra, because of their greater simplicity, are in many cases preferable to the optical spectra, even though the Roentgen spectrum analysis calls for more elaborate equipment. And indeed, by this method several new elements have been detected; as, for instance, rhenium and hafnium (page 100).

While the optical spectra of the elements and their laws had to wait many years for their explanation by the atomic

theory, the discovery of the laws of the characteristic Roentgen spectra was made while the atomic theory was being elaborated so that it could at once be used to confirm this theory. We shall therefore postpone the discussion of these laws, and their importance for elucidating the structure of the atoms, until we can consider them in relation to the atomic theory.

PHOTO-ELECTRONS AND RADIATION QUANTA

When we are sitting in the cinema, and feel pleasure at the truth to nature with which the film reproduces the human voice or musical notes, we hardly stop to reflect that we are really indebted to the atoms, since these are made to give off streams of electrons in time with the sound-oscillations recorded on the film, which streams of electrons, having been magnified thousands of times, operate the loud-speaker behind the screen. This is effected by allowing a beam of light to pass through a film on which, by a special device, there are photographed transversal lines, at varying distances from one another, and varying in blackness, in step with the original sound. The beam of light, whose intensity after passing through the film will vary in step with the sound-waves, is now made to strike upon what is known as a *photo-cell*, in which it detaches from the atoms in a thin film of metal electrons whose numbers are in proportion to its intensity.

This phenomenon of detachment of electrons by light, which has been known to the physicists for many years, is known as the *photo-electric effect*, and is really only a sort of ionization of atoms by the application of light. The detached electrons are often called *photo-electrons*, but are actually quite ordinary electrons. More careful investigations into the phenomenon, however, which were carried out more especially by Lenard in Germany, showed that there were

interesting regularities in the emission which threw a surprising light on the mechanism of radiation.

At first sight there is nothing remarkable in itself in the fact that atoms should lose electrons when irradiated by light, since consideration of the various kinds of ionization will tell us that the electrons are not held so very fast within the atoms. On the other hand, we come upon the most surprising phenomena if we try the effect of variously coloured lights, and measure the speed at which the photo-electrons are given off from the illuminated metal surface.

If we first, for instance, try lighting a sodium surface with green light, and measure the speed of the photo-electrons, we shall find that the electrons are given out with any and all velocities up to a fixed maximum velocity, which is the same whether the intensity of the light is great or small, and this alone is enough to give pause for thought. Even with the weakest green light the maximum speed of the electrons will be exactly the same as when a very powerful green light is used; the only difference is that with a weak irradiation there will not be so many electrons given out as with a strong one. Just as in some countries there is a law restricting the speed of motor vehicles, there would seem here to be a law of nature forbidding the electrons to come forth from the metal at more than a fixed maximum speed.

But the photo-electrons have still greater surprises in store for us, if, instead of the green light, we proceed to employ other colours. If we employ blue light we find that the maximum velocity of the photo-electrons is now considerably greater, whether the illumination is strong or whether it is weak. If we travel further along the spectrum in the same direction—that is to say, if we allow violet or even ultra-violet light to strike upon the sodium surface—we shall find that the detached electrons have a still greater velocity, the maximum limit being again raised; thus it would seem that the higher the oscillation-number of the light, the more

strongly does it act on the electrons. We find confirmation of this if we make the experiment with light having a much smaller oscillation-number, let us say, with red light: for we shall then find that no photo-electrons whatever are set free from the sodium surface, no matter what the intensity of this red light. By now proceeding experimentally with light whose colour lies between red and green we can find that colour whose oscillation-number is just high enough to produce a photo-electric effect.

From these experiments the conclusion may be drawn that light of different wave-lengths or oscillation-numbers has, in addition to its different colour, a further qualitative distinction, which is that the light is apparently able to give up more energy to the individual electrons the greater its oscillation-number.

The velocities reached by the photo-electrons are in general very small compared with the velocities attained by electrons in the case of the β-rays. If the illumination is effected with light of the lowest oscillation-number that still has the power of detaching the electrons, the velocity of these will be simply zero. For measuring the speed of such slow electrons special methods must be employed which are really directed to determining the kinetic energy of the electrons.

Now elementary physics teaches us that a body's kinetic energy is greater in proportion to its weight and its velocity. If we have two bodies with the same velocity, of which one is twice as heavy as the other, then the heavier one will have twice the kinetic energy of the other. If, on the other hand, we have two bodies of equal weight, one of which has twice the speed of the other, then the faster one will have *four* times as much kinetic energy as the other.*

If, therefore, we increase the speed of a motor-car from

* These relations can be expressed by the equation $E = \frac{1}{2}mv^2$, where E is the kinetic energy, m the body's weight, and v its velocity.

50 kilometres to 100 kilometres an hour, its kinetic energy becomes four times as great, so that if the motor is disconnected the car can run four times as far up a uniformly sloping hill before it comes to a stop. The length of the path which a motor-car can travel in this way up a uniformly rising hill with a given gradient gives a direct measure of the kinetic energy which it had at the foot of the hill.

Instead of measuring the velocity of the photo-electrons it will suffice to measure their kinetic energy. To do this we

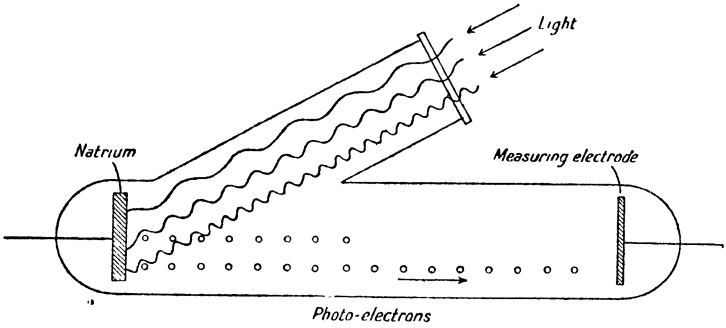


FIG. 14

place an extra electrode, as shown in Fig. 14, in the evacuated glass tube in which the metal plate is illuminated. If this measuring electrode is connected with a sensitive galvanometer the strength of the current which is set up by the photo-electrons can be measured. But if the electrode is given a negative potential it will repel the electrons, and the current will be weakened; and we can now determine that potential which will just suffice to hold back all the electrons, so that no current whatever is flowing. This potential gives us a direct measure of the kinetic energy of the fastest electrons, just as the motor-car running up hill gives us a measure of the kinetic energy of the car. The kinetic energy of the electrons is usually expressed simply by the electric potential which will just bring them to a standstill; thus, for

example, the electrons are said to have a kinetic energy of 10 *electron volts*, if they can just be brought to a standstill by a counter-potential of 10 volts. If, on the contrary, we are dealing with electrons at rest, they can be set in motion by attraction or repulsion of electrically charged bodies. If an electron is repelled from a plate with 10 volts potential, its energy is then 10 electron volts.

Now that we have seen how and in what units the energy of the photo-electrons is measured, we return to our real theme. Exact measurements of the maximum energy of the photo-electrons under illumination by lights of varying oscillation-numbers gave the result that an increase in the oscillation-number caused a proportional increase in the maximum energy of the electrons. Furthermore, it was found that the proportion between the increase in energy and the increase in the oscillation-number had always, and for all metals, exactly the same numerical value; namely, $4{\cdot}1 \times 10^{-15}$, which, therefore, denotes the increase in energy, measured in electron volts, which the photo-electrons receive when the oscillation-number for the light applied is raised by 1.

These phenomena now led to the knowledge of a wholly new property of light. Einstein showed in 1905 that to understand these observed facts we must assume that light-energy can be given up to electrons only in precisely determined instalments or *quanta*, whose amount is equal to the product of the above experimentally determined constant, and the oscillation-number of the light. This can be expressed by the equation:

$$\textit{light quantum} = 4{\cdot}1 \times 10^{-15} \times \textit{the oscillation-number},$$

which, simple as it is, holds within it the knowledge of that new aspect of the nature of light which emerges from the interaction between light and matter.

In photo-electric action the mechanism, therefore, is as

follows: with the liberation of each electron from an atom there is linked one light-quantum of the foregoing amount. It is therefore clear that light having a high oscillation-number gives great energy to the electron. But the electron does not absorb the whole of the light-quantum's energy; part of it is employed in detaching the electron from the atom, which explains why the electrons cannot escape from the metal if the light quanta employed are too small; that is to say, if the oscillation-number is too low.

This discovery, that light-energy can be transformed only into definitely determined energy-quanta, was a very revolutionary one, for it involved an absolute break with the conceptions formerly held as to the nature of light. But the fact must be strongly emphasized that as early as 1900 Planck in Germany had introduced the concept of energy-quanta for explaining certain phenomena in connection with heat-rays which could not be understood in any other way. He was, moreover, able to give the numerical value $4 \cdot 1 \times 10^{-15}$ for the constant which, in accordance with what has just been said, determines the amount of the quanta, and which is, therefore, known as *Planck's constant.* But it was the photo-electric effect and Einstein's interpretation of it, that first gave us an evident and simple proof of the quantum theory of light.

The reason why this property of light had not long before been observed is that the energy-quanta are so infinitesimal that in ordinary intensities of light they are always present in overpowering numbers. If we calculate, for instance, how many energy-quanta are emitted by an ordinary electric glow-lamp, we arrive at a number of the order of 10^{20} light-quanta a second, so that it is no wonder that the human eye cannot take cognizance of this discontinuous quality of light, any more than we can perceive that a drop of water is made up of atoms.

We have now seen how atomic conceptions have gradually

made their way into all departments of physics. First it was matter itself that was found to be built up of atoms. Then it was electricity's turn, with the discovery of the electrons; and now, last of all it has been found that the transformation of electro-magnetic radiation-energy is not a continuous process either, but that it occurs always in quanta.

THE DISCOVERY OF THE ATOMIC NUCLEI

Although the many different physical discoveries which we have hitherto discussed were of the utmost value towards an understanding of the structure of the atom, they were all of a more or less accidental kind. We now come to the first true atomic experiment, carried out deliberately, with the atomic problem kept in view. Through the discoveries described in the foregoing pages it had been definitely established that the atoms must contain electrons and positively charged parts, and exact methods had been found for determining the weight, size and number of atoms.

To obtain a profounder knowledge of how the electrons and the positive charges are distributed throughout the small volume of the atom, the idea was conceived of sending explorers, so to speak, into the unknown country of the atom, and of questioning them after their journey was over. Rutherford in 1911 hit upon the idea of making use of the α-rays proceeding from the radio-active substances to this end, for it is clear that the α-particles, owing to their electrical charge, will, while passing through an atom, be affected and deflected in a way which must depend on the distribution of the charge in the atom. By thus examining into how the α-particles are deflected from their rectilineal paths, we shall be able also to obtain information as to the distribution of this charge. Rutherford then made a close-packed stream of α-particles strike on a gold or platinum foil, which had to be of the utmost tenuity, so that the α-particles could slip through it. On zinc sulphide screens placed close to the metal foil he

now noted, with the help of a microscope, the green flash made by the impact of the α-particles. He then found that, while the great majority of the α-particles passed in a straight line through the metal foil, a small fraction of them suffered deflections which sometimes reached quite considerable amounts. In a very few cases the angle of deflection was as great as 180°—that is to say, the α-particles were thrown back almost along the path by which they had come. Such extreme deflections as these would be quite beyond explanation if we held that the positive charges and electrons were evenly distributed over the whole atom, as we had hitherto been inclined to believe.

Rutherford, on the other hand, showed that the distribution which had been found for the α-particles could be explained by supposing that the whole of the positive charge in the atom, and the whole weight of the atom, except that of the light electrons, were concentrated in a very small space which he called the *atomic nucleus*, and that the electrons circled round this nucleus at distances answering to the outer dimensions of the atom. In the light of this we can understand how the heavy α-particles will, as a rule, make their way without much ado through the gnat-like swarm of the very light electrons, only if the α-particles come very near the nucleus of the atom will the repulsion from this nucleus reach such proportions that the α-particles may be deflected to any extent from their paths.

To illustrate Rutherford's experiment, and his explanation of it, we will imagine that we are standing and firing at a barn-door with a shot-gun. In the great majority of cases the shot will penetrate the door, or sink into it, but once in a while it may happen a shot flies back and hits us. If we then examined the door for the cause of this phenomenon, we should discover that a hard knot or a nail-head had flung back the shot. The reason why such a thing happens but rarely is that there are only a few knots or nails compared

with the whole surface of the door Just as simple in principle, and just as logically explained was Rutherford's experiment, even though he could not directly see the 'knot" in the atoms, but had to infer the existence of the nucleus from the result of the experimental shooting

But from his experiment Rutherford could draw still more exact conclusions From the frequency with which the big deflections were observed he could obtain information not only as to the size of the nucleus of the atom, but also as to the amount of its positive charge, since a heavy charge will, of course, be more likely to produce an extreme deflection than a light charge By careful examination of the distribution of the scattered α-particles in various directions, together with ingenious mathematical calculations, the approximate size and charge of the atomic nucleus were successfully determined

For the diameter of the nucleus of an atom a value was found which for all elements is about 10^{-12} centimetres, that is, about 10,000 times smaller than the outside diameter of the atom which is about 10^{-8} cm If, therefore, we think of an atom being magnified so greatly that the nucleus is the size of an orange, the whole atom will be a third of a mile in diameter The greater part of an atom is thus in reality empty space, so that we can understand how an α-particle can go through many atoms without striking an atomic nucleus

Some years after Rutherford's experiment it was made possible for anyone to convince himself with his own eyes that Rutherford had seen aright, for Blackett in England, with the help of a cloud-chamber, succeeded in photographing the paths of α-particles which were deflected by striking the nuclei of the atoms of the gas in the cloud-chamber Fig 15, Plate III, page 78, shows such a photograph of the passage of α-particles through ordinary air, in it we see an individual α-particle colliding with an oxygen nucleus, whereby the

α-particle is sharply deflected to the left, while the short fork rightward is traced by the oxygen atom, which was set in motion by the collision As the oxygen atom is heavier than the α-particle it does not acquire so great a velocity from the collision, so that its path is shorter than that of the α-particle Fig 16, Plate III, page 78, shows a highly interesting collision between an α-particle and a helium nucleus, which was contrived by filling the cloud-chamber with helium It will be noticed that the two branches in the path are at a right angle to each other, which is explained by the fact that the α-particle and the helium nucleus have exactly the same weight Those of our readers who play billiards will perhaps have noticed something like this, for two billiard balls of equal weight, after colliding, run off in directions that are precisely at a right angle Owing to the infrequency with which a nucleus is hit, Blackett had to take a great many thousand cloud-chamber photographs before he succeeded in obtaining one picture of a nucleus in collision

Through the interpretation of his experimental bombardment of the atom Rutherford was led to take the view of atomic structure which is known as the *Rutherford model of the atom* According to this the atoms of all the elements would be built up in the same way, with a heavy positive nucleus at the centre and electrons circling round it, so that they would form a kind of Lilliput solar system, with the nucleus as the sun and the electrons as planets The number of electrons must naturally be exactly the same as the number of positive elementary charges in the nucleus, so that the atom as a whole may be electrically neutral As has been already said, Rutherford, from the diffusion experiments, was able to find an approximate value for the number of the positive elementary charges in the nucleus, and he found a number which, for the heavy substances investigated, was a little under half the relative atomic weight of the element, and which was greater in proportion to the atomic weight For gold, to take an

example, which has the atomic weight 197, he found the nuclear charge to be 79.

If the elements are arranged in a series with rising atomic weights, it seems almost obvious that this serial order will also represent the rising nuclear charges. The lightest atom of an element, the hydrogen atom, must thus be assumed to be made up of a nucleus with one positive elementary charge, and with one electron circling round it. The next lightest atom, the helium atom, must have two positive charges in the nucleus, with two electrons circling round. Next to it comes the metal lithium, which is conceived as having the nuclear charge 3 and 3 electrons; and so forth. According to this hypothesis the number in the series of elements—*the atomic number*—would at once give us the number of positive elementary charges in the nucleus of the atom of the element concerned, and so, also, the number of electrons in the atom's outer system of electrons. This view, which in the beginning was no more than a sheer hypothesis, proved later on to be of the greatest importance for understanding the physical and chemical properties of the elements.

Through the investigations described in the foregoing section, and particularly through Rutherford's discovery of the atomic nucleus, the view came to be accepted that the atoms, and with them all matter, were built up of small positive and negative particles, though it was not at all clear what were the natural laws governing the mutual interaction between these particles. In particular, the laws of the line spectra and of photo-electric action were quite beyond understanding from the standpoint of the hitherto known fundamental physical laws, which had been determined through experiments with bodies of so great size and weight that we could not expect that they would apply unconditionally to the individual atoms.

In the series of great discoveries which laid the foundations of atomic physics we are dealing here only with the most

important. Many particulars of significance and interest have necessarily been omitted, so that the picture which we have sought to draw of the standpoint of atomic physics just before the fateful year of 1913 is not given in all its detail, but it is, we hope, despite the broad strokes of the brush, a sufficiently accurate likeness.

II

The Outworks of the Atoms Fall

SCIENCE, in its progress towards an ever deeper knowledge, follows many different sorts of paths. It is generally believed that its advances are made solely along the lines of the great epoch-making discoveries, but we must never overlook the fact that in the periods between the great discoveries important work is always being done, in which the foundations are laid for these discoveries by a steady revision of measurements and calculations. Then at last there comes a time when science makes a sudden leap forward, when some research worker of genius arises who with his lucid vision is able to grasp as a whole the investigations and discoveries of the preceding years. Such a comprehensive grasp is usually accompanied by an immense advance in science, for we now have the power to continue our researches more systematically, and are no longer compelled to work in the dark, as so often happens. Moreover, the wider outlook thus achieved will commonly open up entirely new fields of research.

BOHR'S ATOMIC THEORY

A leap of this kind in the growth of atomic physics was made in 1913, when Niels Bohr in Denmark put forward his atomic theory. Bohr took Rutherford's model of the atom for his starting-point, and by a stroke of genius he linked this up with the remarkable discovery made by Planck and Einstein, that the radiation-energy in certain phenomena is emitted or absorbed by matter in precisely determined energy-quanta.

And, indeed, Rutherford's atomic model itself was soon found to clash with the general laws of physics as hitherto

known; as will easily be seen if we consider a little more closely how, for instance, a hydrogen atom built up after Rutherford's model will behave according to these laws. As we have already said, a hydrogen atom, according to this model, is made up of a nucleus with one positive elementary charge, round which revolves an electron, much as a planet revolves round the sun. Since the law for the electrical attraction between nucleus and electron is identically the same as Newton's universal law of attraction which governs the planets' motions round the sun, the electron's path around the nucleus will be an ellipse with the nucleus at one of the foci, or, as a special case, a circular orbit, with the nucleus as centre.

In the atom, however, as compared with the solar system, there is this great distinction: the electron is electrically charged, and this means that it must be constantly radiating electro-magnetic waves, since every electric charge whose velocity changes its rate or direction must needs radiate such waves. This radiation must be constantly taking energy from the atom, with the result that the electron begins to move in ever shorter and shorter paths, so that in the end it falls into the atomic nucleus. An atomic pattern such as this must have its energy at the maximum when the electron is at its farthest from the nucleus, and its energy will be at the minimum when the electron is following an orbit close to the nucleus, and the nearer the electron's orbit lies to the nucleus, the more work will be needed to detach the electron from the atom. But as the electron draws nearer to the nucleus, so will it revolve faster and faster, and therefore the oscillation-number of the radiation emitted will become higher and higher. In other words, according to the ordinary physical laws an atomic system such as this would radiate, in a moment of time, the whole of its stock of energy, in the form of electro-magnetic waves with steadily lessening wave-lengths; and this could not be reconciled at all with the fact

that the atoms send out light of fully-determined and sharply-defined wave-lengths. But worst of all, such an atomic system could not possibly be stable, but within an infinitesimally short period of time it would shrink to a volume the size of the atomic nucleus, which is in glaring inconsistency with the fact that the atom has a remarkably stable structure, with a diameter about 10,000 times as great as that of the nucleus.

Thus for a moment the outlook was black for Rutherford's atomic model, until Bohr formed the daring conclusion that it was not the atomic model which was incorrect, but, on the contrary, that it was the ordinary electrical, magnetic, and mechanical fundamental laws that broke down when they were applied to single atoms. How bold a conclusion this was will be understood when we bear in mind that these laws, which make up the whole of what is known as classical physics, not only summed up the experience and discoveries of the centuries, but were also the foundation of the whole of modern technology, and, above all, of our highly-developed electro-technology. Bohr, however, was the first to recognize that the laws of classical physics cannot be unquestioningly applied to the world of atoms, but that within the atoms quite other laws hold sway, conditioning the stability of the atoms.

The recognition of this fact found its full expression in the first of the two celebrated postulates on which Bohr founded his theory of the atom. The first postulate lays it down that: *An atom can exist only in fully defined states—what are known as the stationary states—in which the atom possesses a fully-defined amount of energy, no radiation being sent forth so long as the atom finds itself in these states. The emission or absorption of radiant energy from an atom can occur only when the atom changes over from one such stationary state to another.*

In this postulate it is therefore expressly declared that the oscillating electrons, in a stationary state of the atom, do

not obey the command of classical physics, to send out radiation. This refusal to obey the classical law makes it possible for the atoms to maintain their stability; on the other hand, the number of the electrons' revolutions in the stationary states of the atom has no longer anything to do with whatever radiation the atom may send out. On the contrary, Bohr assumed that the radiation was emitted in energy-quanta, just as Planck found in the case of heat-radiation. This Bohr set forth in his second postulate: *The radiation sent forth or absorbed by an atom through its passage from one stationary state to another has an oscillation-number which is determined as follows: the oscillation-number multiplied by Planck's constant is equal to the difference in the atom's energy in these two stationary states.*

Bearing in mind that the product of Planck's constant and the oscillation-number makes an energy-quantum, we can express the content of the second postulate by saying that one energy-quantum is released each time an atom makes the passage from a state having a high energy-content into another with a lower energy-content. If these two states show a great difference in energy, the quantum sent out, and so also the oscillation-number will be large, so that we have an emission of light with a short wave-length, while a small difference of energy will give light with a long wave-length. Conversely, by irradiating an atom with light of a suitable wave-length we can make the atom take up one energy-quantum, whereby it goes over into a stationary state with correspondingly greater energy.

This postulate thus directly relates the wave-length of the emitted radiation with the state of energy of the atom, so that we may hope to obtain from the spectra some knowledge concerning the energy of the atoms in the stationary states. Now, Rydberg's and Balmer's investigations into the laws of the line spectra have told us that the oscillation-number is always found to be a difference between two quantities,

whose nature had hitherto been an enigma. In accordance with Bohr's second postulate these quantities, when multiplied by Planck's constant, $4 \cdot 1 \times 10^{-15}$, give an immediate expression for the energy-content in the different stationary states of the atom. Since this holds true for all atoms, we are able by spectroscopic measurements to determine the state of energy for any atom. In particular, for the hydrogen atom we find from Balmer's formula (see page 51) that the different numerical values for the energy, measured in electron-volts, are given by the product

$$\frac{3 \cdot 3 \times 10^{15}}{n^2} \times 4 \cdot 1 \times 10^{-15} = \frac{13 \cdot 5}{n^2}$$

n being taken through the series of whole numbers.

Since the hydrogen atom is assumed to consist of a nucleus and one electron, these different amounts of energy in the atom are simply an expression for the *energy of detachment* which must be supplied, when the electron is in the state of energy in question, in order to remove it altogether from the atom. The different values for the energy of detachment in the stationary states of the hydrogen atom are therefore given by the following series of numbers:

$$\frac{13 \cdot 5}{1}, \frac{13 \cdot 5}{4}, \frac{13 \cdot 5}{9}, \frac{13 \cdot 5}{16}, \frac{13 \cdot 5}{25} \text{ and so on.}$$

In particular the lines in the Balmer series are emitted through the atom passing from higher stationary states with $n = 3, 4, 5, 6$ and so on to the stationary state with $n = 2$, which has the energy of detachment $\frac{13 \cdot 5}{2^2}$, the oscillation-number for the emitted lines being found by taking the differences

$$\frac{13 \cdot 5}{4} - \frac{13 \cdot 5}{9}, \frac{13 \cdot 5}{4} - \frac{13 \cdot 5}{16}, \frac{13 \cdot 5}{4} - \frac{13 \cdot 5}{25}, \frac{13 \cdot 5}{4} - \frac{13 \cdot 5}{36}$$

and so on, and dividing these by Planck's constant $4 \cdot 1 \times 10^{-15}$, whereby we obtain the oscillation-numbers of the Balmer series.

If, however, we attempt a more exact theoretical treatment of the stationary states in the hydrogen atom, which of course must be the simplest possible atom, we shall find ourselves in the peculiar position of being apparently unable to make any calculation whatsoever, since we have nothing to start from. By accepting the postulates we have, indeed, broken down all the bridges behind us, and have altogether forsaken the firm foundations offered us by the classical mechanics.

In order that we may go forward, we will make ourselves guilty for the time being of something that looks like the greatest of inconsistencies. We shall pretend that the laws of ordinary mechanics do hold good for a hydrogen atom, and so we shall try to calculate the electronic paths which have those exact detachment-energies which correspond with various stationary states of the hydrogen atom. A calculation such as this is extraordinarily easy to make, since the charge and mass are known both for the electron and for the positive hydrogen nucleus. It is then found that the electron, to have a detachment-energy (or ionization potential) of $13 \cdot 5$ electron-volts must move in a circular path with diameter 10^{-8} cm., which indeed agrees very well with the results found for the size of an atom from other purely experimental investigations. This, therefore, would be the diameter for the electron's orbit in the first stationary state of the hydrogen atom, if the premise for the calculation were correct. In the same way, we find that the diameter of the path corresponding to the detachment-energy $\frac{13 \cdot 5}{4}$ volts is $2^2 \times 10^{-8}$ cm., that is to say, four times as great, which, therefore, would be the diameter of the orbit in the second stationary state of the hydrogen atom. For the third stationary state we find that the diameter of the orbit would be $3^2 \times 10^{-8}$ cm., and so on.

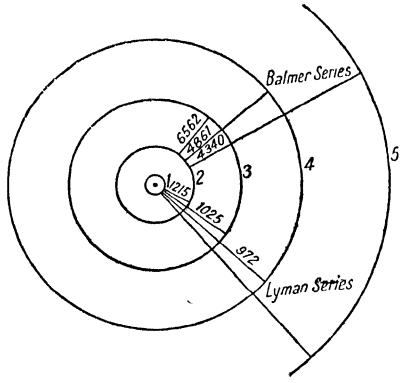
Now that we have once begun to apply the laws of classical

mechanics in spite of Bohr's postulates, we will cast all hesitation aside, and proceed to calculate with what velocity the electron revolves in these "stationary" orbits. In the result we find that the electron in the first orbit, where the diameter of the orbit is 10^{-8} cm., makes $6{\cdot}6 \times 10^{15}$ revolutions of the orbit in a second. In the next orbit, which is four times as long, the electron can make "only" $0{\cdot}82 \times 10^{15}$ revolutions to the second; or, to be more precise: The number of revolutions is $8 = 2 \times 2 \times 2$ times less than that for the first orbit. For the third orbit, which is 9 times as great as the first, calculation shows that the number of revolutions is $3 \times 3 \times 3 = 27$ times less than the number in the first orbit; and so on.

But it must be always stressed that these numbers of revolutions have nothing whatever to do with the oscillation-number for the spectral lines of hydrogen, of which we can easily convince ourselves by setting the calculated number of revolutions against the oscillation-number of the lines in the Balmer series. The first of these lines, that is to say; the red hydrogen line with wave-length 6562·80 Å, has an oscillation-number of $0{\cdot}43 \times 10^{15}$ hertz, while the next line, with wave-length 4861·38 Å, has the oscillation-number $0{\cdot}61 \times 10^{15}$ hertz.

These calculations for electron orbits, though indeed they are partly based on false premises, have the advantage that we can obtain quite a definite picture of the different stationary states of the hydrogen atom. In Fig. 17 are depicted the first of the "stationary" electron orbits which we have just calculated, the black dot in the middle marking the nucleus of the hydrogen atom. It is seen that the dimensions of the orbits increase at a very rapid rate, the diameters being in the ratios 1 : 4 : 9 : 16, and so on. In the diagram lines have been drawn, linking the different orbits, which show the transitions at which the lines of the hydrogen spectrum are emitted. We see that the lines of the Balmer

series correspond to transitions from paths $n = 3, 4, 5$, and so on, to path $n = 2$. And lastly, there are shown transitions from paths $n = 2, 3, 4$, and so on, to path $n = 1$, these corresponding to a wholly new series of lines in the hydrogen spectrum.* This series, whose existence became very probable in the light of Bohr's theory, was found a few years later by Lyman in America, in the outermost short-waved ultra-violet part of the spectrum, which is difficult to examine.



1 Å
10^{-8} cm.

FIG. 17

But all these considerations as to electron orbits and the numbers of the revolutions in the hydrogen atom had unfortunately the tiresome defect of being based on the supposition that the laws of classical mechanics can be applied to the atoms, and we know for certain that this is not generally true. If these considerations, in spite of this, are set forth here it is because they offered the only possible way of making any advance in understanding the atomic structure, and also because they held, as Bohr pointed out, not a little of the truth.

* The oscillation-number $= \frac{3{\cdot}3 \times 10^{15}}{1^2} - \frac{3{\cdot}3 \times 10^{15}}{n^2}$, $n = 2, 3, 4, 5$, and so on.

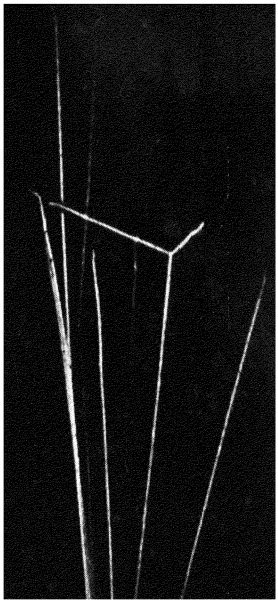


FIG. 15. - Cloud - chamber photograph of a "nucleus-hit," where an α-particle strikes the nucleus of an oxygen atom.

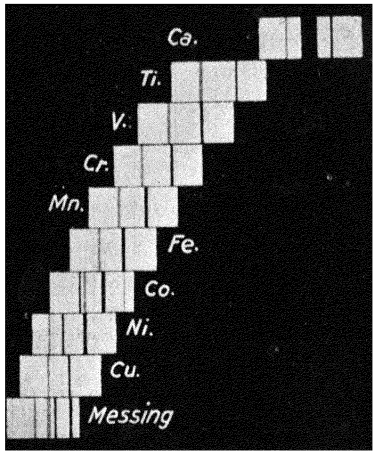


FIG. 19.—Characteristic Roentgen spectra after Moseley, arranged according to rising atomic numbers from calcium with atomic number 20 to copper with atomic number 29, with the exception of No. 21, scandium. The lowest spectrum, of the alloy brass, shows the lines of the alloy's constituents copper and zinc (No. 30).

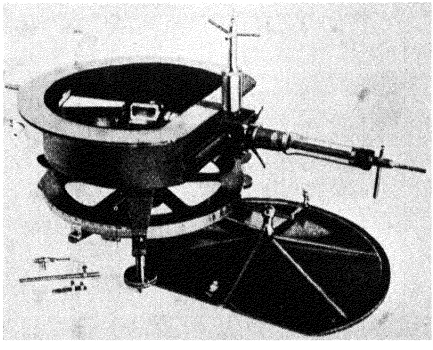


FIG. 20.—Vacuum Roentgen spectrograph after Siegbahn. The crystal is seen in the centre of the spectrograph.

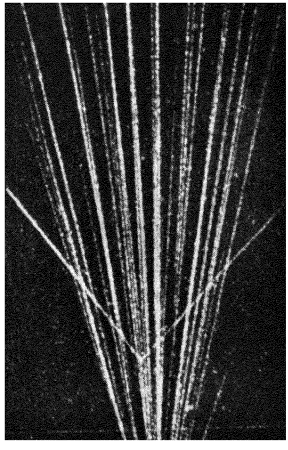


FIG. 16.—Cloud-chamber photograph of the collision between an α-particle and a helium nucleus.

PLATE IV

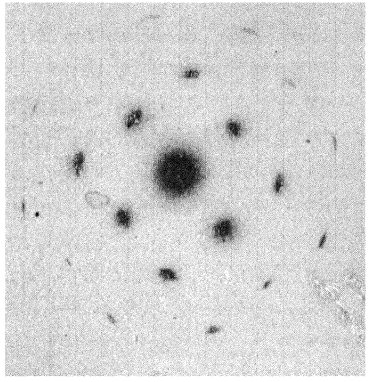


FIG. 23. Photograph of the interference of electrons when passing through a platinum crystal.

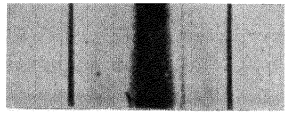


FIG. 26.—Photograph of the red spectral line of hydrogen taken with a long exposure. Close to the right of the heavily blackened line is seen a very weak spectral line from heavy hydrogen.

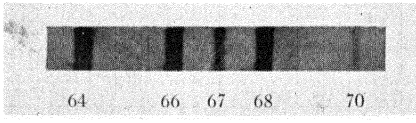


FIG. 25.—Mass spectrogram of zinc's five isotopes. 64, 66 and 68 are those found in greatest quantity, 67 in less, and 70 in very small quantities, as is seen from the blackening.

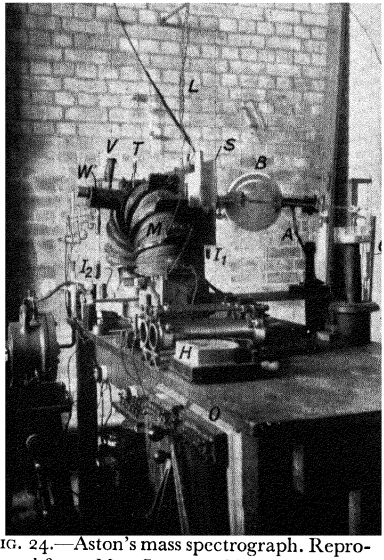


FIG. 24.—Aston's mass spectrograph. Reproduced from *Mass Spectra and Isotopes*, by kind permission of Messrs. Edward Arnold & Co.

A. Anode connected to high potential terminal of induction coil below table.
B. Discharge tube.
C. Reservoir containing gas to be analysed.
G. Gaede rotating mercury pump connected to the camera and the discharge tube by glass tubes and stopcocks.
H. Magnet circuit ammeter.
I_1, I_2. Charcoal-liquid air tubes exhausting slit-system and camera.
L. Leads from high-tension battery to electric plates.
M. Du Bois electromagnet.
O. Magnet circuit control resistances.
S. Soft iron plates to shield discharge from stray magnetic field.
T. Pea lamp for photographing fiducial spot.
V. Vacuum-tight and light-tight control for moving photographic plate.
W. Camera showing light-tight cap on left.

Bohr, then, laid stress on the fact that there must be a gradual transition from the laws of ordinary physics to those laws which hold good for the atoms, so that there must be a field in which *both* these groups of natural laws hold sway. This borderland will be found, as far as the hydrogen atom is in question, if we examine electron orbits with very great values for n, for then the orbits come to have dimensions that are quite within our grasp. For example, the path for $n = 1000$ will then have a diameter of $1000 \times 1000 \times 10^{-8}$ cm. $= \frac{1}{10}$ mm. For very great values of n we are thus fully entitled to make the aforesaid calculations of the number of revolutions, and to regard this as equal to the oscillation-number for the light emitted. On the other hand, in this field Bohr's second postulate also holds good, which gives directly the oscillation-number of the light emitted on transition between two neighbouring orbits of the said dimensions.

Since the calculated number of revolutions depends on the charge and mass of the electron and the hydrogen nucleus, Bohr was now able, by making the number of revolutions equal to the oscillation-number found by the second postulate, to write an equation which allowed the Rydberg constant to be calculated by the sole help of the known values for Planck's constant, and for the charge and the mass of the electron and the nucleus. This calculation gave a value of $3 \cdot 3 \times 10^{15}$ hertz, in full agreement with the value for the Rydberg constant which had been found by spectroscopic measurement. This was the first great triumph for Bohr's theory, for something of the mysticism which had hovered over the Balmer formula was now cleared away, and the fundamental atomic oscillation, which the Rydberg constant in reality represents, was linked up with properties belonging to the stones that build up the hydrogen atom.

Bohr's calculation for the Rydberg constant is particularly remarkable, as being, mathematically, perfectly exact; and

it is so because the calculation is based upon the fact that there is a transitional field wherein both the classical mechanics and the atomic mechanics hold good. This, however, implies further that the calculation of all the orbits in the hydrogen atom has a certain approximate truth, and no more, so that there is something to be said for making use of the graphic conception of the orbit whenever extreme exactness is not required.

The emission of light from a hydrogen atom may therefore be graphically represented in the following way: In an undisturbed hydrogen atom the electrons will travel along the innermost orbit ($n = 1$), and we say that the atom is in its *normal state*, in which the detachment-energy is equal to 13·5 electron-volts. By electrical discharges or a high temperature the atom can be "moved on"; that is to say, the electron is brought out to a wider "stationary" orbit, from which, after a short interval, it falls back into a shorter orbit, or right into the innermost one, sending forth a light-quantum; and the emission of light will not stop until the atom has again reached the normal state. A hydrogen atom which is moved on to a given state will therefore not emit all the spectral lines of hydrogen, but at most only a few, which are produced as the electron, on its way in towards the normal state, makes a stop in one or more of the stationary orbits. When, however, in the light of a discharge tube containing hydrogen, the whole of the hydrogen spectrum can be seen, this arises from the fact that such an immense number of atoms are moved on to different states that all possible transitions between the different states are realized.

Such considerations as these, however, hold good not only for the hydrogen atom, but for every atomic system with only one electron. Such a system can be obtained, for example, by ionizing a helium atom, which normally contains two electrons. If we remove one of these the atom

becomes a positive ion, made up of a doubly charged nucleus with one electron circling round it. An ion of this kind will send forth light-quanta when the remaining electron, after having been moved on to longer orbits, returns again into shorter orbits. The spectral lines emitted must form series, just as in the hydrogen spectrum, only with the difference that the Rydberg constant, owing to the double nuclear charge, is altered. Bohr showed, by just the same calculation as for the hydrogen atom, that the Rydberg constant for an atom whose nucleus has a fairly large number of positive charges increases as the square of this number, so that for the spectrum of the helium ion we must have a Rydberg constant four times as great as the ordinary one.

Before this many of these spectral lines had been observed in the spectra of certain stars, but the belief had been held that the lines came from hydrogen, for they had been found only along with the lines in the Balmer series. After Bohr had shown that the lines had their source in the helium ion, the experimental physicists succeeded in producing the spectrum from a terrestrial source of light, by sending very powerful electric discharges through pure helium, by which means the atoms were both ionized and moved on.

As a result of the Rydberg constant being multiplied by four the detachment-energy for the different stationary states in the helium ion is given by the following series of numbers:

$$\frac{4 \times 13{\cdot}5}{1^2}, \frac{4 \times 13{\cdot}5}{2^2} = 13{\cdot}5, \frac{4 \times 13{\cdot}5}{3^2}, \frac{4 \times 13{\cdot}5}{4^2}$$

$$= \frac{13{\cdot}5}{4}, \frac{4 \times 13{\cdot}5}{5^2}$$

and so on; from which it is seen that each other one of these states has the same detachment-energy as the states in the hydrogen atom (see page 76). We might therefore expect that some of the spectral lines for the helium ion

would fall on the hydrogen lines. The experiments, however, showed that these lines did not wholly coincide, but that there was a slight divergence. But Bohr was able at once to give an explanation of this by taking into account, in his calculations, the circumstance that the atomic nucleus is not at rest during the electron's revolution, but goes through a motion at the same time, which, however, is smaller in proportion as the nucleus is heavier. Since the helium nucleus is heavier than the hydrogen nucleus, the calculations show that the Rydberg constant for helium is not exactly four times what it is for hydrogen, but 4·016 times as great, which exactly corresponds with the differences between the spectral lines in question.

The explanation fitted so well that since then the problem has been turned about, so that by precisely measuring these differences in wave-length between the hydrogen and the helium lines we can determine the ratio between the mass of the hydrogen nucleus and that of the electron. This is for that matter one of the most exact methods we have for determining this ratio, and we find that the hydrogen nucleus is 1838 times heavier than the electron (cp. the other method for determining this ratio, page 38).

There is furthermore a whole series of atomic systems made up of one nucleus and one electron; for example, the double-charged lithium ion, that is, a lithium atom that has lost two of its three electrons, and the treble-charged beryllium ion, which is a beryllium atom that has lost three of its four electrons; and so on. According to Bohr's theory, the Rydberg constant for the spectra of these ions must increase as the square of the nuclear charge, so that for the lithium ion it will be $3^2 = 9$ times, and for the beryllium ion be $4^2 = 16$ times as great as for the hydrogen atom, if we disregard the very small change arising from the greater weight of these atomic nuclei. The oscillation-numbers for the spectral lines from these ions can therefore be found at once from the

spectral lines of hydrogen by multiplying the latter by nine or sixteen respectively, so that we obtain correspondingly shorter wave-lengths, situated very low down, near the wave-lengths of the Roentgen rays. A few years ago, by applying very powerful electric sparks, the strong ionization of the atoms that was needed for detachment was successfully effected and their spectral lines were photographed, when it was found that they had exactly the wave-lengths that were foretold by Bohr's theory.

It is therefore always without exception true that an atomic system made up of a nucleus with charge N, round which revolves one electron, has a Rydberg constant which is N^2 times as great as that of hydrogen. The stationary states for a hydrogen-like ion such as this have therefore detachment-energies which are obtained from the expression:

$$N^2 \times \frac{13 \cdot 5}{n^2}, \text{ putting } n = 1, 2, 3$$

and so on.

If now we try to apply Bohr's theory to atomic systems containing several electrons, the situation is, of course, a more complicated one, yet there are certain features in the spectra of all atoms which allow of a very simple interpretation by this theory. As was said above, Rydberg showed that the same numerical constant, $3 \cdot 3 \times 10^{15}$, was always found in the spectra of all the atoms. Bohr's explanation of this was that even in the more composite atoms one of the electrons only is mainly responsible for emitting the spectrum, just as in the hydrogen atom. This electron, known as the *optical electron*, may be more strongly or less strongly linked with the atom, thereby giving rise to the formation of stationary states, with energies whose differences yield the oscillation-numbers of the emitted spectral lines, in accordance with Bohr's second postulate. The other electrons, on the other hand, are assumed, in all these states of energy, to

travel in the same defined paths. If the orbit of the optical electron comes to be very great compared with the paths of the other electrons, it will resemble a corresponding orbit in the hydrogen atom, since the negative charges of the other electrons, together with the positive charge of the nucleus, will then, practically speaking, have the same effect as a nucleus with only one positive charge. The considerations set forth above, by which Bohr was able in the case of the hydrogen atom to express the Rydberg constant by Planck's constant, and the charge and mass of the electron and the nucleus, could therefore just as well be applied to the optical electron in any atom whatsoever. As a result of this the assumption of an optical electron explains the fact that the Rydberg constant for hydrogen appears in the spectra of all the atoms.

For the present we will not weary the reader with further spectroscopic results, but will only stress the fact that these results, owing to the exceptional accuracy of spectroscopic measurements, have played a leading part as touchstones for the atomic theory. As the main conclusion we can assert that Bohr's atomic theory has taught us to interpret the spectroscopic results for stationary states in the atoms, so that from the spectrum of any element we can calculate the energy-content for all stationary states in this element's atom.

THE ATOMIC THEORY WINS ITS WAY

Bohr's atomic theory, when it was first advanced, met with not a little opposition, owing to its revolutionary assumptions, although its opponents had no choice but to bow to the great body of proof to be found in the spectroscopic data to which we have just referred. But this body of proof was soon further increased by new experiments, of which the most convincing was a direct measurement by electrical methods of atomic energy in the stationary states.

Let us first consider the order of magnitude of the amounts of energy which we have to measure. The detachment-energy for the first stationary state of the hydrogen atom was, according to Bohr's theory, equal to 13·5 electron volts, which is therefore the energy that must be supplied to the hydrogen atom so as to detach the electron from the normal state and remove it altogether from the atom. In the same way the energy can be calculated that is needed to bring about a transition from the basic state to one of the higher states, and which is known as the *impact energy* (radiation potential). This is done simply by reckoning the detachment-energy for the higher stationary states and subtracting this from the detachment-energy of the normal state. For example, for the two consecutive states in the hydrogen atom we find respectively $\frac{13\cdot5}{4} = 3\cdot4$ volts and $\frac{13\cdot5}{9} = 1\cdot5$ volts, so that the impact energy for these states is $13\cdot5 - 3\cdot4 = 10\cdot1$ volts and $13\cdot5 - 1\cdot5 = 12$ volts. Since the detachment-energy for the higher stationary states diminishes sharply towards zero, the impact energy for higher states rapidly approaches equality with the detachment-energy of the normal state, which is 13·5 volts, and is known also as the *ionizing energy* of hydrogen.

We see therefore that the energies which we have to measure are of the same order of magnitude as the electronic energies which we had to consider in the case of the photo-electrons, and therefore the methods of measurement that must be used here will be of the same kind as those used for the photo-electric effect.

These direct measurements of the impact energy and the ionizing energy of atoms were carried out for the first time by Franck and Hertz in Germany in 1913–14; on practical grounds, however, they did not select hydrogen atoms as the experimental object, but chose mercury atoms. The principle of the experiment consisted in bombarding the atoms

with electrons having a determined velocity, and thus a determined kinetic energy. There was then a chance that the electrons might collide with some of the atoms, and in so doing yield up some of their energy; when by measuring the loss of energy from these electrons we should ascertain the quantity of energy which was yielded up to the atoms.

The apparatus employed was more or less on the principle of a radio tube or valve, consisting of a glass container (see

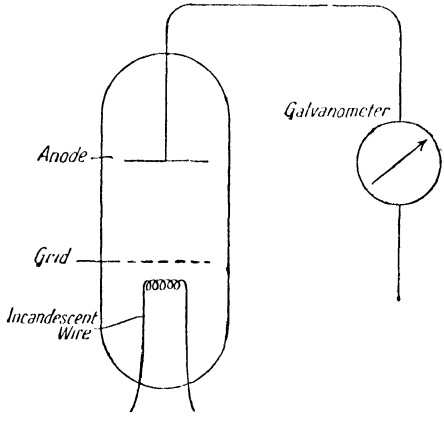


FIG. 18

Fig. 18) wherein was an incandescent wire, a grid, and an anode, connected with a galvanometer, so that the electron-stream could be measured. The electrons sent forth from the incandescent wire could be given the desired velocity by setting the grid at a determined potential in relation to the incandescent wire, when some of the electrons collided with mercury atoms, the tube being full of mercury vapour. When the accelerating grid potential was now gradually raised, it was found that the stream of electrons to the anode increased, just as in an ordinary radio valve, uniformly with the increasing velocity of the electrons; but suddenly, when the potential passed 4·9 volts, the stream fell steeply to a far

lower value, and when the grid tension was further raised the stream began once more to increase. This remarkable result could be explained only by assuming that part of the electrons with this energy of 4·9 electron-volts were beginning to yield up their kinetic energy to the mercury atom; since a certain minimum velocity of the electrons is obviously needed to raise the mercury atoms from the normal state to the next following stationary state. The electrons, therefore, must have yielded an energy of precisely 4·9 electron-volts to the atoms. This energy, to the great joy of the friends of the atomic theory, exactly agreed with the value for the lowest impact energy of the mercury atom which had been worked out from the mercury spectrum.

These experiments in electronic collisions were soon enlarged to include many other substances, and they were not confined to measuring the impact energy for the lowest stationary states, but by means of a refined technique it was found possible to measure both the impact energy for the higher states, and also the ionizing energy. For all the elements investigated complete agreement was found with the energy values which on Bohr's theory could be worked out from the observed spectra of the atoms concerned. These investigations therefore showed incontestably that Bohr's postulates were universally valid.

Later on similar experiments in electronic collision were successfully carried out with hydrogen, when it was found that the ionizing energy was exactly 13·5 volts, as had been calculated from the hydrogen spectrum. For comparison we may mention that the ionizing energy for a helium atom is 24·46 volts, for a mercury atom 10·4 volts, and for a lithium atom 5·4 volts, the ionizing energies for all elements lying between about 4 and about 25 volts (cp. Fig. 22, page 99).

By an interesting variation of the procedure in this experiment, the spectrum of the light emitted by the bombarded atoms on falling back to the lower states was likewise observed. This was

done in the case of various substances, by taking a series of spectrum photographs of the light between the grid and the anode while the speed of the electrons was gradually increased. These photographs showed that with the lower potentials on the grid only a very few spectrum lines were visible, while new spectrum lines showed themselves at exactly those potentials which had been calculated from Bohr's theory.

The experiments with electronic collisions thus gave full support in every respect to Bohr's theory, and at the same time gave us a deeper understanding of what goes on when an atom is ionized.

THE ORIGIN OF THE ROENTGEN SPECTRA

In all departments of physics there now arose new problems which had to be investigated in the light of the atomic theory. And the Roentgen spectroscopists came forward with new results and asked for an explanation of the remarkable recurrent features which they had found in the characteristic Roentgen spectra of the elements.

Bragg in England was the first to succeed in developing Laue's method for determining the wave-length of the Roentgen rays by interference in crystals: he made the first Roentgen spectrograph, wherein the Roentgen rays were made to form a spectrum on a photographic plate, so that their wave-length could be measured without difficulty. Another English physicist, Moseley, undertook in 1914, with the help of such a Roentgen spectrograph, a systematic examination of the characteristic Roentgen spectra of the atoms. He found that these spectra did not after all answer to their various names, for the appearance of the spectrum was almost unchanged on proceding from one substance to another, the only dissimilarity being that the wave-lengths were slightly different. Fig. 19, Plate III, page 78, shows a series of Moseley's photographs, in which we see the "characteristic" lines shifting towards shorter wave-lengths when

the atomic weight becomes greater. By exactly measuring the wave-length for these lines Moseley was now able to find a surprisingly simple relation between the oscillation-number and the atomic number of the substance, that is to say, its number in the atomic series, the oscillation-number for (let us say) the strongest line in the spectrum being found to increase in proportion to the square of the atomic number.

This law, known as *Moseley's Displacement Law*, was at once explained by Bohr, who assumed that these Roentgen spectrum lines arose from the passage of electrons from one orbit to another in the atom, when these orbits are nearest the nucleus. For these innermost electrons the attraction by the nucleus will be all-powerful in comparison with the repulsion by the other electrons, so that their state of energy will be very nearly the same as if all the outer electrons were removed. We can thus without more ado apply Bohr's results for ions of the hydrogen kind. For these we saw (see page 83) that when the nuclear charge was N elementary charges, the stationary states had detachment-energies which are found from the expression $N^2 \times \frac{13{\cdot}5}{n^2}$ by putting $n = 1$, 2, 3, and so on. Dividing by Planck's constant, we then find, in respect of the light-quantum emitted on the electron's passage between the two innermost paths ($n = 1$ and $n = 2$), in an atom having nuclear charge N, that the oscillation-number $= N^2 \times 3{\cdot}3 \times 10^{15}\left(\frac{1}{1^2} - \frac{1}{2^2}\right) = \frac{3}{4} \times N^2 \times 3{\cdot}3 \times 10^{15}$.

This at once explains the law discovered by Moseley, by which the oscillation-numbers increase as the square of the atomic number, if in accordance with the earlier assumption we *identify the atomic number with the number of elementary charges in the nucleus*. At the same time, the formula gave a very close approximation to the measured oscillation-numbers when the numerical value for the atomic number N was substi-

tuted. As an example, for a substance such as copper, where N is 29, the strongest Roentgen line has a wave-length of 1·5 Å—that is, an oscillation-number of about 2×10^{18} hertz—while with Bohr's formula, by substituting $N = 29$, we find the oscillation-number $2 \cdot 1 \times 10^{18}$ hertz.

This agreement is all the more striking in that Bohr's original theory had nothing whatever to do with the Roentgen spectra, having been worked out for the optical spectra, whose wave-lengths were thousands of times greater than those of the Roentgen rays. The agreement shows, therefore, that Bohr's general principles for the emission of light from atoms hold good also for conditions within the atom. Even the small divergence between the calculated and the observed oscillation-number can be understood, for it arises from the fact that we cannot *wholly* disregard the action of the other electrons, whose negative charge, even inside the atoms, will in some degree offset the positive charge of the nucleus, so that in calculating the oscillation-number we ought really to substitute a slightly smaller value for the nuclear charge N than the true atomic number 29.

If now we consider an undisturbed atom with many electrons, we have to imagine these electrons not as revolving round the nucleus of the atom in utter confusion, but as being, on the whole, distributed among the stationary paths, which in a hydrogen atom or in an ion of the hydrogen kind are characterized by the numbers $n = 1, 2, 3, 4$ and so on. Normally such an atom will not send out any radiation, but if in one way or other an electron happens to be wanting, let us say in the innermost orbit, then the possibility will exist that an electron may pass over from other orbits into the innermost one, whereby the various lines in the Roentgen spectrum are emitted. Things happen here as they generally do in life when a vacant position has to be filled; that is to say, there is promotion from the post next below, which then becomes vacant, and is itself filled up by promotion, and so

on. It may happen, too, that promotions through several steps occur, but these are more infrequent. Just so, in the atom the transition from the innermost orbit but one ($n = 2$) is that which happens oftenest, and it is therefore this that gives rise to the strongest line in the Roentgen spectrum, whose oscillation-number is determined by the formula given above. On the other hand, the transition from the third path ($n = 3$) to the innermost one will be much less frequent, so that the corresponding line with the higher oscillation-number* and the correspondingly shorter wave-length is a good deal weaker, as can be seen in Fig. 19, where the left-hand line for each substance is the weakest.

We may now expect that it will be possible for Roentgen lines to be emitted with longer wave-lengths. Thus, if an electron is wanting in path $n = 2$, then by the transition of an electron from orbit $n = 3$ or $n = 4$ to orbit $n = 2$ radiation may be emitted with a wave-length corresponding to the smaller differences in energy of these orbits. Such spectrum-lines have, indeed, been investigated by Siegbahn in Sweden, who has developed Roentgen spectroscopy to the highest degree of perfection, and has made precise measurements for the Roentgen spectra of all substances. These long-waved Roentgen rays are very "soft" in comparison with the short-waved rays: that is to say, they have a very low penetrative power, so that they cannot even get through the air. Siegbahn had therefore to make special vacuum spectrographs, in one piece with the Roentgen tube, so that the rays could pass unhindered from the anti-cathode to the crystal and thence to the photographic plate. In Fig. 20, Plate III, at page 78, we see one of these vacuum spectrographs, where the Roentgen tube is screwed fast on the front, while the lid is taken off from the spectrograph itself so that the crystal and the plate-holder can be seen. From

* The oscillation-number $= N^2 \times 3{\cdot}3 \times 10^{15} \left(\frac{1}{1^2} - \frac{1}{3^2}\right) = \frac{8}{9} N^2 \times 3{\cdot}3 \times 10^{15}$ hertz.

Siegbahn's investigations valuable information was obtained as to how the electrons in the various atoms are distributed along the various possible orbits, answering to $n = 1, 2, 3 \ldots$

The first condition for the production of a Roentgen spectrum is, therefore, that an electron should be detached from one of the inner orbits in the atom For this, however, we must have an energy corresponding to the detachment-energy for an electron in the orbit in question, that is, for example, for the innermost orbit we must have an energy of $N^2 \times 13\ 5$ electron volts For a substance such as copper, where the atomic number N is equal to 29, we obtain from this an energy of about 10,000 electron-volts, while for a substance such as wolfram ($N = 74$) we need about 70,000 volts Since the Roentgen rays are produced by bombarding the substance with electrons, these latter must have a kinetic energy that is at least equal to the said detachment-energy if by collision they are to displace the innermost electron in the atom The numerical examples given show, therefore, the lowest potential which we must apply to our Roentgen tube if we wish to produce the Roentgen spectrum lines in question, and this, indeed, corresponds with experience, since it is always found that we have to apply a certain minimum potential if we are to get a determinate line

It was therefore possible by Bohr's theory to explain the laws of the Roentgen spectra in all their details, although Bohr was originally thinking only of the optical spectra when he stated his theory That the theory was able to comprehend the whole of this new field of experiment was naturally one of the strongest proofs that what it told us about the structure of the atom was very largely true

THE CARD-INDEX OF THE ELEMENTS AND THE ATOMIC NUMBER

Natural scientists are often orderly people, for a great part of their work is done by putting together and classifying

their results in such a way that the most disparate facts are brought together under common heads This, however, is not due to mere pedantry, but is linked up with the fact that Nature herself, in all her manifold productions, is seen to be governed by laws, which as a rule are first revealed only when the results of the investigators have been reduced to systematic order The best-known example of this is perhaps to be found not in physics but in botany, where Linné in Sweden was able to introduce system into the almost infinite number of variations shown by the vegetation of the earth.

But in physics and chemistry also the same efforts have been made, in respect of the various elements and their properties, ever since the chemists succeeded in showing that all matter was made up of some ninety different elements with quite definite properties In the last century Mendeleyev in Russia and Lothar Meyer in Germany found that these elements could be arranged in what is known as a *Periodic System* they showed that when the elements are arranged in a series of rising atomic weights, certain definite chemical and physical properties recur at certain periods as we proceed through this series But this was strictly and wholly true only if it was at the same time assumed that there were certain gaps in the series, corresponding to elements which had not yet been found Mendeleyev, over and above this, was able to forecast some of the properties of the missing elements so exactly that on the basis of his forecast these elements were sought for and were found This was enough to put beyond a doubt the importance of having such a *card-index of the elements*, for this is what the periodic system really is

But it was only after the development of the atomic theory that we began to perceive the fundamental laws which are the basis of the periodic system, and succeeded in filling up several of the gaps by the discovery of new rare elements The most important instrument in this physical revision of the card-index of the elements was Roentgen spectroscopy,

and especially the displacement law found by Moseley for the Roentgen spectra of the elements. For on the basis of this law it was extraordinarily easy to complete the serial order of the elements, since any substance which might be missing would at once make itself known by a seemingly excessive shifting of the spectrum lines at that point in the series of elements at which this substance is missing (cp. Fig. 19). Moreover, Bohr's theory of the Roentgen spectra enables us directly to determine the nuclear charge of an atom, and therefore the atomic number, when we know the oscillation-number of the Roentgen lines. A systematic review of all the Roentgen spectra gave not only information as to which elements were still wanting, but also information as to the true atomic numbers of the elements. While before this the elements had been arranged in the order of their increasing atomic weights, it was now obvious that they ought to be arranged in the order of the increasing nuclear charges, so that the regular change in their properties should be clearly shown in the periodical system. As a matter of fact, it was found that with very few exceptions the two methods of arranging the series of the elements yielded the same serial order.

Fig. 21 shows the periodic system of the elements. With each substance is given the atomic number and the chemical symbol before the name of the element; the substances are arranged in seven series, known as the *Periods*, within which the chemical properties vary from substance to substance more or less in the same way. Those elements whose properties show reciprocal likeness are joined by a line. For example, the substances which begin each series, that is, the metals lithium, sodium, potassium, rubidium and caesium, known as the alkali metals, are very closely akin to one another, their similarity showing itself, amongst other ways, in their common tendency to form positive ions, giving off one electron, and in the great similarity between the optical

electron is much more loosely linked to the atom than are the two others, if we are to understand the already mentioned tendency of lithium to form singly charged positive ions We assume, therefore, with Bohr that the first electron group, corresponding to $n = 1$, is closed by helium, and that a new group, corresponding to $n = 2$, starts with lithium Substance No 4, beryllium (nuclear charge 4, number of electrons 4), has in agreement with this theory a tendency to form doubly charged positive ions, that is to say, the two outermost electrons of the new group are given up by the atom with particular ease It will be found that this new electron group does not, like the first, close with two electrons, for the following substance, boron, which has nuclear charge 5, and 5 electrons, forms trebly charged positive ions, and therefore contains three comparatively loosely bound electrons

Proceeding thus, we find that the next substance, carbon, which tends, when interacting with other substances, to give off 4 electrons, also forms chemical combinations, which shows that the carbon atom is given to *capturing* 4 electrons from other substances when the opportunity occurs For the following elements this latter tendency becomes outstanding, and nitrogen, oxygen and fluorine readily take up 3, 2 and 1 electrons respectively, whereby the sum of electrons in all three cases becomes 10 Substance No 10, neon, is, like helium, highly stable, and has no inclination to form either positive or negative ions, which strongly suggests that electron group $n = 2$ is complete with this element, which is able to contain 8 electrons This is immediately confirmed by substance No 11, sodium, which, like lithium, has one very loosely held electron, and is the first in the group with $n = 3$ Within the second period the first substances ($N = 3, 4, 5$) have a tendency to give up all the second group's electrons, while the last substances in the period ($N = 7, 8, 9$) readily make up the number with so many electrons that the group ($n = 2$) becomes completed

The increase of the electrons occurs in just the same way in the third group, when we go through the third period of the series, from sodium to argon. On the other hand, things are a little more involved in the following periods, of which both the fourth and the fifth are seen to contain 18 elements. In these periods we note in the table that certain elements are shown in a specially drawn frame, as these substances are unlike some of the preceding substances. The same thing is found in the sixth and seventh periods, but here matters are still more complicated. These peculiarities can be explained by the atomic theory, but it would take us too far afield to go into details. We will only say here that the explanation is due to the fact that in the higher electron groups there are also sub-groups which are sometimes filled in only after the next following main group has begun. For instance, it is only a sub-group of the third main group ($n = 3$) that is filled in with argon, as on filling in the fourth main group, the group ($n = 4$) has already begun with potassium and calcium. The special properties found in the framed substances following (21–28) are now explained by the completion of the interrupted main group ($n = 3$). The substances framed within a period are distinguished by the fact that among themselves they are not very different, chemically considered; which is understandable, since it is an inner electron group that is being filled in, while the number and grouping of the outer electrons, which in the main determines the chemical properties of the substance, is almost constant within the section of a period thus framed. This fact finds particularly striking illustration in the substances included in the innermost framed section of the seventh long period—known as the *rare earths*—whose properties are so alike that chemists find it very hard to distinguish them.

In this survey of the periodic system we have spoken only of the *chemical* properties of the substances, but exactly the

same result would have been reached if we had made use of the spectra of the substances in examining the electronic distribution in the various groups. We will content ourselves here with comparing the detachment-energy for the outermost electron in the atoms of the different elements, which has been determined partly from the spectra of the substances, and has also been measured directly by the elec-

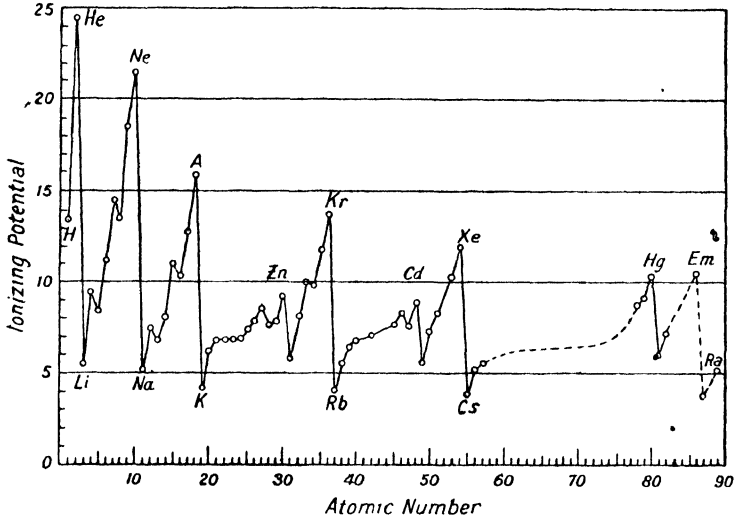


FIG. 22

tronic collision method. Fig. 22 shows how the ionizing energies measured up to now vary within the element series, the atomic number being marked off along the horizontal line, and the corresponding ionizing energy in electron volts being read on the perpendicular to the left. For example, we see that radium, which has the atomic number 88, has an ionizing energy of 5·1 volts. It is also obvious that the noble gases make the mountain-tops and the alkali metals the depths in the line joining all the points marked, which shows clearly that the electrons in the noble gases are bound

fast, while the outermost electron in the alkali metals is very loosely held.

In accordance with what has now been said it will be seen that the distribution of the elements in determinate periods of the element series is based on the fact that the various electron groups in an atom are able to hold only a limited number of electrons, which number determines the length of the periods.

A deeper understanding of why these groups should hold just 2, 8, 18, etc., electrons, was obtained from the theoretical researches of Pauli in Austria. He discovered a rule (Pauli's Exclusion Principle) which limited the possible number of electrons in each group to $2 \times n^2$. If in this expression we put $n = 1, 2, 3 \ldots$ we get the numbers 2, 8, 18, 32 and so on, which are in harmony with the actual facts.

Before we pass on from this field of research, in which we perceive the beauty and harmony revealed by Bohr's masterly interpretation of the periodic system of the elements, we must mention that practical results have been obtained. A good example of such results is the discovery of the element *hafnium*, which was a direct consequence of the newly-won knowledge of the electron grouping in atoms. It was known for certain from the Roentgen spectra (Moseley's law, p. 88) that substance No. 72 was missing in the series of the known elements, but that, of course, was not the same as finding it. It was believed, indeed, that the group of rare earths (see Fig. 21) must include this substance, and therefore, because of the rarity of these substances, and their great similarity to one another, that it would be difficult to find it. On the other hand, it could be inferred from Bohr's theory that the sub-group of the rare earths must be bounded by substance No. 70, so it might be expected that substance No. 72 would show similarities to zirkon, and it must therefore be presumed that it existed in Nature along with this latter. Guided by these considerations, Coster in Holland

and v. Hevesy in Hungary tried analysing zirkon minerals by the Roentgen spectroscopic methods, when they at once found spectrum lines at those places where, according to Moseley's law, such lines were to be expected for substance No. 72. This substance, which was named *hafnium* after Copenhagen, which is called Hafnia in Latin, was discovered on closer examination to be an element occurring in abundance, and having precisely the properties forecast by the theory.

The picture of atomic structure, as it was unfolded before the eyes of the natural scientists by the elaboration of Bohr's atomic theory, was naturally far more detailed than can be shown in these pages. For the atomic theory makes itself felt in many more fields than those here mentioned, and is able to account on broad lines for the greatest variety of phenomena. One of the main articles of the theory is that almost all the physical and chemical properties of substances have their source in the outer electron system of the atoms. Both the optical characteristics and the electrical and magnetic properties of the elements, as well as their more or less active tendency to enter into chemical combinations, are all properties conditioned by the number and the distribution of the electrons in a given atom. There are only two properties of substances which are independent of the electronic system, and which must be referred to the atomic nucleus—the weight of the atoms, and radio-activity.

It must, however, be stressed that indirectly the atomic nucleus is responsible for the building up of the electronic system, and so also for the properties of the element, since the nucleus, by its electric charge, determines the number of electrons in the system. This is why we cannot change one element into another merely by removing one of the outer electrons of the atoms, since the atomic nucleus will at once endeavour to catch a new electron, and again build up the original atom. If, on the contrary, an alteration occurs in

the nuclear charge, it will automatically be followed by a corresponding change in the number of electrons, whereby a new element is actually formed. Since we have already seen that radio-activity always brings with it a change of element, we must draw the conclusion that the charged particles sent out by radio-active substances come from the atomic nuclei, so that the charge of the nucleus is altered.

When a radio-active substance sends forth α-particles, which have two positive charges, we shall expect the nuclear charge, and with it the number of electrons in the atom, to be diminished by two, so that there is formed a new element, which lies two places back in the periodic system; and this, in every case, has been confirmed by physical and chemical investigation. As an example of this process let us look a little more closely into the transformation of radium into radium emanation. The metal radium, which has the atomic number 88, shows, in harmony with its place in the periodic system, marked chemical similarities to the metals calcium, strontium, and barium. By the emission of α-particles it is transformed into Ra emanation, which is a gas with properties very like those of the noble gases, and which, therefore, must occupy place No. 86 in the periodic system. In exactly the same way, we find that the emission of a negatively charged β-particle from a nucleus increases the positive charge of the nucleus by 1, so that the daughter product lies one place further along in the system.

When we look at the many radio-active substances in the genealogy of the radium family as shown in Fig. 1, we shall perhaps wonder why all of them are not given, along with the other radio-active substances, at the very end of the card-index to the elements. This seeming lack of order in the last drawers of the card-index, however, cannot be set right until our last chapter, when we shall learn of wholly new properties in the atomic nuclei; and this involves a further classification in the drawers of the card-index to the elements.

ATOMIC MECHANICS AND A LITTLE PHILOSOPHY

In Bohr's first postulate it was very strongly stressed that the fundamental physical laws hitherto known have only an approximate validity for the atoms. When Bohr's atomic theory was none the less able to show such brilliant victories, this was partly owing to the fact that the laws become fully valid again when they are applied to very high stationary states, but more especially to the fact that the postulates already held within them the most essential features of the new laws that prevail in the atoms. What still remained to be done, however, was by giving the correct generalization to the laws of classical physics to reach the goal of those wholly exact natural laws which have unconditional validity both in the macroscopic world and within the atoms, and which, among other things, should enable us, from our knowledge of the building-stones of the atoms, and the forces between them, to calculate the energy in the stationary states for all possible atoms. Before we investigate the exact quantum mechanics which has yielded the solution of this problem, we will mention an extension of the atomic theory by Goudsmit and Uhlenbeck in Holland in 1925, and which led to the establishment of new fundamental properties for the electrons.

It had long been known that some lines of the spectrum showed what is known as a *multiple structure*: for example, all the lines in the sodium spectrum are double, while in other spectra we find trebled or quadrupled lines. According to Bohr's postulates it was clear that these so-called doublets, triplets, quartets, and so on must arise from the corresponding stationary states in the atoms consisting in reality of several contiguous states; but of the fundamental cause of this nothing whatever was known.

Goudsmit and Uhlenbeck now put forward the hypothesis that all atomic electrons had the property of revolving upon

themselves like tops, a property known as the electron's *spin*. The motion of an atomic electron can therefore be roughly imagined by picturing an old-fashioned couple waltzing round a ballroom in a wide circle, while at the same time they turn round upon themselves. Just as the dancing couple can revolve clockwise or can reverse, so also a light electron may spin in either direction. Now the electron has an electric charge, and since it is an axiom of physics that any electrically charged rotating body behaves exactly as an ordinary magnet, the electron, both because of its spin and because it is revolving in its orbit, will have magnetic properties. The electron, therefore, accordingly as it waltzes clockwise or conversely in a given orbit, will by reason of the magnetic forces in operation give rise to two different stationary states, whose energy will be slightly different. Since the spectra of the metals lithium, sodium, potassium, and so on result mainly from one loosely-held light electron, we thus have an explanation of why the spectrum lines of all these substances are double. The more complicated triplets, quartets, and so forth in the spectra of other substances may likewise be explained by the electron spin, if it is borne in mind that several electrons may be at work together in the emission of the spectrum.

We will now return to the more detailed elaboration of atomic mechanics, a problem which has been attacked by various theoretical physicists, and by widely varying mathematical methods. It was W. Heisenberg of Germany in 1925 who first was able to expound what is known as *quantum mechanics*, which attacked the problem at its root by ruthlessly excluding any magnitude from the theory which could not be experimentally observed. Thus quantum mechanics does not comprise any such conceptions as that of the orbit of the electrons in a stationary state, or the electron's period of revolution. On the contrary, Heisenberg's original theory made use only of those conceptions which are found in

Bohr's postulates, such as energy-content and the oscillation-numbers of the energy-quanta. Since, however, this theory calls for a very high degree of mathematical knowledge, we shall not examine it in greater detail.

A widely different procedure was followed by de Broglie in France (1924) and Schrödinger in Austria (1926), who both started with a wholly new conception of the nature of the electrons. De Broglie assumed that electrons, and in general all material particles, can under certain conditions behave as though they were waves.* There were, however, not many who accepted this assumption at the time, for it did not seem possible to reconcile it with the conceptions which had hitherto been formed of the nature of electrons, based on experiments in the deflection of cathode rays, photographs taken with the Wilson cloud-chamber, Millikan's experiment, and so on.

There were, however, a few physicists who were bold enough to carry out experiments with electrons to see whether it would be possible to produce the phenomenon of interference characteristic of all kinds of waves. Davisson in America in 1927 and G. P. Thomson in England in 1928 succeeded in doing this. The method was to let a cluster of electrons with an exactly known velocity strike a crystal. By placing a photographic plate in close proximity to the crystal, as in Laue's experiment with the Roentgen rays, the actual presence of interference was successfully established, it being found that the electrons were reflected only in fully determinate directions, just as though Roentgen rays of a determinate wave-length were being employed. On making measurements of the photographs of the interference pattern it was found that the corresponding wave-length depended on the velocity of the electrons, so that a high electronic

* To particles with mass m and velocity v there corresponds a wave-length $\frac{h}{mv}$, where h is Planck's constant.

velocity corresponded with a small wave-length, which was exactly what might be looked for in accordance with de Broglie's theory. For an electron which has, for example, passed through a potential of 100 volts the theory gives a wave-length of about 1 Å; that is, the same as for the ordinary Roentgen rays.

But we must not think that the waves here considered have the same physical reality as light-waves. Electromagnetic waves, like light-waves, are made up of changing electric and magnetic forces, which in principle can be measured with electric and magnetic instruments; but there is no question of any such thing in the case of the de Broglie waves. These waves are only a convenient method for expressing how the electrons behave while passing through a crystal, the different interference maxima being merely the places which in such an experiment are struck by electrons, while the minima are the places where no electrons occur. The experiments furthermore show that the position of the interference-spots is wholly independent of the number of electrons in the electron-ray. If this number is very greatly diminished, so that, for example, there should come only one electron a minute, we must imagine that these electrons, after being deflected in the crystal, will always strike one of the interference-spots. On the other hand, it is impossible to say beforehand on which one of the spots each particular electron will strike. We can at most ask how great is the likelihood of an electron striking a given spot, for the de Broglie waves make it possible to calculate this very probability.

Before we go on to discuss the epistemological consequences that are to be drawn from the interference experiments, it must be firmly grasped that this phenomenon must be accepted as proved beyond all doubt by countless and varied experiments. As an example of this we see in Fig. 23, Plate IV, page 79, a photograph of the interference-spots for electrons

which have passed through a platinum crystal: in this we recognize a striking likeness to the Laue photographs of Roentgen rays (Fig. 13). But this must not stand in the way of our holding fast to the usual conceptions of the electrons as small particles with definite weight, charge, and magnetic properties, directly we are dealing with experiments other than those performed with crystals. As we shall consider in more detail, the reason why the original conceptions do not work properly for the crystal experiments is merely the fact that the crystals are built up of atoms whose distances from one another are as small as 1 Å or thereabouts: that is to say, of about the same dimensions as the wave-length of the de Broglie waves, whereas in all the earlier electron experiments described there was plenty of room for the electrons to move about in.

As we shall now perceive, we can draw a highly remarkable conclusion from these facts, for we shall find that it is beyond our power to determine at one and the same time, with complete accuracy, both the position of an electron in space and the magnitude and direction of its velocity. If, therefore, we measure the exact position of an electron, the determination of its velocity can be made with only a low degree of accuracy, and conversely, an exact measurement of its velocity will mean unexactness in determining its position. As we shall see, this limitation does not arise from imperfection in the measuring instruments, but is something that follows directly from the natural laws which emerge in the interference experiments. The discovery of this fact brings with it an utterly new attitude towards nature, since the application of the classical mechanical laws is in fact conditioned by our being able to determine at the same time a particle's velocity and its position with as great a degree of accuracy as is desired.

If this new discovery were to be true for the phenomena of everyday life, one result would be, for example, that it

would be impossible for the traffic police to state at the same time both the position of a motor-car and its exact speed. But in order to reassure the agents of the law we should add that the inaccuracies arising from the facts stated are infinitesimally small when compared with the inaccuracies arising out of the use of stop-watch and tape-measure. But, as we shall now see, a very different state of things obtains in the world of the atoms, and especially as regards the lightest particles of all, the electrons.

To go more closely into these phenomena, which have remarkable consequences for the theory of knowledge, we will think of a highly simplified experiment with electrons having a given velocity, which we cause to strike upon a sheet in which there is a small orifice whose diameter is the same as the de Broglie wave-length of the electrons. Such an experiment is naturally only an imaginary one, since, firstly, a hole cannot be bored with a diameter of 10^{-8} cm., and, secondly, no substance would be dense enough for the purpose, for all matter, being built up of atoms, is porous like a sieve with holes of just this size. This, however, does not in any way weaken the validity of the conclusions which we wish to draw from our imaginary experiment, for the electrons must naturally always behave like waves, even if they are offered only one hole instead of the many that are found between the atoms in a crystal.

We must first, for a moment, let classical physics tell us how waves behave in a general way when they are forced to go through a tight opening, that is, an opening whose diameter is not much greater than the wave-length. We choose light-waves for this purpose, but the results are so general that they hold good for all waves. As a rule, a beam of light falling at right angles onto a sheet in which there is a small orifice will form a sharply defined spot, the size of the orifice, on a screen placed behind it. But this is true only when the hole is large in comparison with the wave-

length of the light. If we make the hole smaller and smaller, so that we come down to a small fraction of a millimetre, the light-spot on the screen will gradually increase in size, the light being more strongly diffracted around the edge of the hole, as this grows smaller.

To return to our electrons: these, because of their wave-properties, will be diffracted just like light-waves around the edge of the tiny hole, so that a photographic plate put behind the hole will be blackened at a spot which will be bigger, the smaller the hole is made. If we now imagine that the perforated sheet is bombarded with fewer and fewer electrons, still having the same velocity, so that, for example, one electron a minute passes through the hole, the image of the deflection, as in the experiments on crystallic interference, must remain unchanged. The electrons will therefore fall now on one place, now on another within the deflection-spot, and nothing can be said beforehand as to where the electrons will strike than that they must fall within this deflection-spot. For any one electron there will be, therefore, an indeterminateness, which cannot be calculated beforehand, in the electron's motion after its passage through the hole.

With this we already get a glimpse of the fundamental impossibility of which we have just been speaking, of determining simultaneously the velocity and the position of an electron within any degree of accuracy which we may choose to define. Let us first assume that we have complete knowledge of our electron's velocity, as regards both measure and direction, and that we wish to know something about its position. We naturally resort then to the same methods as those which we should employ if we knew that a herring was swimming in the Channel at a speed of 50 kilometres an hour, direction due north, and if we wanted to localize it a little more exactly. In such a case we should stretch a seine across the Channel. If the herring swims into the net,

we have then determined its position. To localize the electron, which is absolutely invisible, we therefore put our screen with the small aperture across the direction of the electron's motion. If the electron goes through the hole, then we have obtained some knowledge of its position, at all events as far as two dimensions go.

But this knowledge of the electron's position has been reached only at the cost of our knowledge as to the direction of its motion, since after the electron has gone through the hole we can no longer say, owing to its deflection, exactly in what direction it will be moving. If we increase the degree of exactness of our determination of the electron's position —that is, if we make the hole in the screen smaller—by so doing we lessen the exactness of our knowledge as to the direction of its motion. If on the other hand the hole is made so large that hardly any deflection occurs, this means that the direction of the electron after its passage through the hole will have been determined with great precision, but to make up for this our uncertainty in determining its position then becomes great, for we cannot tell at what point in the hole the electron passed through it, but only that it passed through one or another point in the opening. The indeterminateness in the electron's position is thus inversely proportional to the indeterminateness in its velocity, so that the one is high when the other is low, and conversely. This relation, known as the *Principle of Indeterminacy*, has been expounded by Heisenberg, and more closely discussed and applied in its pregnant consequences by Bohr, who has described the phenomena represented by the concepts velocity and position as *complementary*, since, while in certain respects they exclude each other, yet each expresses an essential aspect of the behaviour of particles.

Bohr in particular has laid stress on the circumstance that this *complementary relation* depends in the end on the fact that in every phenomenon for whose process Planck's constant

is the determinant there is a reciprocal effect, which is beyond our observation, between the atomic objects concerned and the measuring instruments employed for observing the phenomena. Since on principle this reciprocal effect can never be brought below a certain limit, which is fixed by this very Planck's constant, we find that it is impossible, in the case of atomic phenomena, to distinguish between the independent behaviour of the objects and the influence of the measuring instruments.

In the imaginary experiment described above, when an electron passes through a small aperture, there appears to be a reciprocal effect which is beyond our observation between the electron and the perforated sheet which serves to localize the electron, and which itself gives rise to the deflection of the electron. The deflection and therefore the amount of the reciprocal effect was, however, conditioned by the fact that the de Broglie wave-length of the electrons was equal to the dimensions of the hole, the deflection diminishing as the wave-length diminished, and it would disappear altogether if the wave-length were zero. From the expression for the wave-length (see footnote to p. 105) we see, therefore, that this reciprocal effect arises from the fact that it is Planck's constant, small though it is compared with ordinary processes, which determines the process of atomic phenomena.

While such a complementary relation was something quite new in physics, this same relation is well known in various fields of human life; for example, we come upon such a complementary relation if we have to write a book such as this. What we have to do is to make the treatment of the subject as clear and readable as possible, and this necessarily means that we must forgo all the details and the exact scientific expression which are found in specialist literature, which for the layman is anything but easy to read. There is, therefore, a complementary relation between lucidity and detailed treatment, so that the degree of lucidity is high if only a few details are given, and conversely. However, both clearness and detail alike are needed if an exhaustive de-

scription is to be given, but the two things cannot both be obtained at the same time. Our task, therefore, is always to make such a choice that we strike the right balance between these two complementary conceptions.

The peculiar situation which has arisen owing to our being forced to make use of the conception of the complementary relation in physics has as its result that in the description of individual atoms and electrons we shall be able only to a limited extent to find a use for the conception of causal determination. The use of causal determination in physics consists, indeed, in this: that from the knowledge of the velocity and the position of particles at one determinate moment we can reckon these magnitudes for any later moment of time we may choose, when the forces acting on the particles are known. But since, as a result of the Principle of Indeterminacy, we cannot know at one and the same time both the velocity and the position of particles with any degree of accuracy we may choose, it is clear that the conditions for applying the conception of causal determination are not fulfilled. This is sure to be a stab in the heart to many, and it may be that there are still many philosophers of the old school who have hopes that with finer methods of measurement we shall succeed in getting a more precise determination of the position and velocity of particles than that which the Principle of Indeterminacy grants us.

We shall try, however, by making use of one of Bohr's imaginary experiments, to make it clear how absurd it would be that it should really be possible, in spite of the Principle of Indeterminacy, to determine a particle's position and motion with unlimited precision. If, then, we imagine a sheet with *two* small holes in the path of a stream of electrons, instead of the one hole hitherto employed, the circumstances are quite different. Thus, from the theory of light we know what will happen to waves that are passing through two such holes: instead of a bright spot on the screen behind the holes

we shall see a set of alternate bright and dark bands. Quite simply, there is interference between the waves from the two holes, the length of the paths from any point on the screen to the two holes being different. The bright bands show where the waves have reinforced one another, while the dark bands show where they have weakened one another. If, on the other hand, we cover one of the two holes, we get no interference bands, but only the usual deflection spot. We see, therefore, that the image on the photographic plate is greatly modified when instead of one we have two holes in the screen.

If now we make use of electrons in an experiment like this, the result will be just the same as with light, for we know that electrons as well as light can set up interference, and so on a photographic plate we shall get an image showing alternate dark and bright bands. If we were really in a position to determine an electron's velocity and position with any desired precision before it passed through the holes, we should then, as a result of causal determination, be able to know through which hole in the screen it would pass, and where it would strike the plate. We might think that all the electrons of which we know—let us say—that they will go through the lower of the two holes should naturally remain unaffected by our closing or not closing the upper hole. But what the experiment does show is that if we close the upper hole, the electrons that pass through the lower hole will strike the photographic plate at quite different places from those on which they struck before, since the electrons in this case will give us only a deflection-spot instead of the bands of which we have spoken. But since it will clearly be against reason to assume that electrons which we know are going to pass through the lower aperture should be able to notice whether the other aperture is closed or not, there is then no other possibility open than to acknowledge that the phenomena with which we are dealing cannot be classified in the custom-

ary way, which can only be applied when we have to do with phenomena in which we can neglect the interaction between the objects and the measuring instruments, and in which the usual causal conception can therefore be applied.

Before we go on to the more positive results of atomic mechanics, it will perhaps not be out of place to consider the results which we have just been discussing in the light of the philosophers' old quarrel between the determinists and indeterminists. The former, as we know, hold the view that existence is pre-determined, or at all events, that each and every state of things can be forecast by applying the conception of causal determination, if we know how things are at a given point of time. The indeterminists, on the other hand, deny the possibility of any such forecasting, as they foresee the intervention of unknown forces. Formerly the majority of physicists were probably determinists in their philosophical attitude, since, indeed, the whole of classical physics was a great and brilliant example of the rightness of the principles of determinism. But now that we have seen the results of the quantum theory the case is altered, though not so far as to convert the physicists to indeterminism; such an attitude, indeed, would mean the utter surrender of any possibility of the study of physics. What has happened is only that it has been realized that it is fundamentally impossible to determine exhaustively all those factors which have hitherto been deemed necessary for establishing the physical state of things at a given point of time; so that the conditions of determinism cannot be regarded as fulfilled within the world of atoms. Yet this does not mean that physics has become less exact, but only that regular processes of a new character have been found, which fall outside the boundaries which had been marked out by the conception of causal determination, but which find their natural place inside the wider frame for the description of Nature which corresponds to the standpoint of the complementary relation.

THE LATEST TRIUMPHS OF ATOMIC MECHANICS

Contrary to the earlier conceptions, in which the stationary states of the atoms were made intelligible by means of electronic orbits, the foregoing results imply that, just as in the case of electronic interferences, so within the atoms we can speak only of probabilities for finding determinate positions for the electrons. In the interference experiments these probabilities were described with the help of the de Broglie waves. Schrödinger then succeeded in finding the equation—"the Schrödinger equation"—which in every case governs the diffusion of these "waves" in space and time; and it was found that this equation could account for the existence of the stationary states in atoms. For these states it must hold true that the probabilities for the position of the electrons concerned do not change with time. If now we examine whether there are such stationary solutions for the Schrödinger equation, we find that for each atom there exists a whole set of solutions, to which we therefore ascribe the various stationary states in the atom. From the Schrödinger equation we can also find the energy of the atom in these states, and this is seen to be in agreement with the energy-values found from the spectra and from Bohr's second postulate. Even for more complicated atomic systems it was possible to carry out calculations which in every case were in gratifying agreement with the experimental results.

In the Schrödinger equation, however, no heed was taken of the electron's spin, so that this equation did not give all energy-values which produce the delicate structure of the spectra. From a purely theoretical standpoint the Schrödinger equation had the further defect that it did not take into account the corrections that might be expected from Einstein's theory of relativity in connection with the high velocities of the electrons in the atom. According to this theory, whose treatment falls outside the scope of this book,

an electron would seem not always to have the same weight, but to behave as though it became heavier in proportion to its velocity. For slow electrons this correction has no importance, but when the electron's velocity approaches the velocity of light, the electron's mass increases very rapidly, and would become infinitely great if the electron could actually reach the velocity of light.

Dirac in England now succeeded in killing two birds with one stone: he put forward a new equation for the de Broglie waves, which not only took into account the corrections of the relativity theory, but also gave the very number of stationary solutions which we must expect as the result of the electron's spin. With this the theoretical treatment of the mechanics of the atoms had been brought to a fine conclusion, for Dirac's theory, difficult though it was owing to its abstrusely mathematical character, was yet able to account in every detail for the interaction between an atom's parts.

There was only one seemingly great drawback to Dirac's theory, which was, that besides the set of solutions corresponding to the experimentally found stationary states, it also provided an unlooked-for set of solutions which corresponded to a series of stationary states in which the electrons had to behave as though they had a negative kinetic energy, and therefore a negative mass. A negative mass would, however, mean that the electrons, if acted on by a force, would move *against* the direction of the force, a mode of behaviour which led a playful theoretician to give the electrons in these states the name of "donkey electrons." The experimental physicists, however, had never known electrons to behave in such a manner, but this might perhaps be due to the fact that the electrons never made their appearance in these states. The difficulty was now that as a result of Bohr's second postulate we had to expect that there might be transitions between these two groups of stationary states, so that a usually well-

behaved electron, by such a transition, might be turned into a "donkey electron."

Either Dirac's theory had now to be wholly rejected—which would have been a great pity, for it was, indeed, capable of explaining the facts in all their details—or else a reason had to be found why these transitions could not happen. So Dirac assumed that all the negative stationary states were normally filled up with electrons, so that there was not, so to speak, any room for more, just as the different electron-groups in the heavier atoms can hold only the number of electrons fixed by Pauli's principle. On this assumption, then, the possibility of transitions to the "negative" states is normally ruled out.

According to these conceptions empty space would be filled up with infinite multitudes of electrons with negative energy. Since empty space is electrically neutral, and has zero energy, we have to suppose that these "donkey electrons" cannot, in principle, be observed. If, on the other hand, in some way or another, one of these electrons has been made to transfer to the normal electrons' field of positive energy, there might then be a possibility of observing both this electron and the "hole" thereby made in the field of negative energy. Such a hole must have the same properties as an electron with a positive charge, and with the positive energy which an electron would have, since, if we are to reach the normal state again, for the empty space we must add a negatively-charged electron with negative energy. The hole on this hypothesis would have the same motion under the influence of electric or magnetic forces as a positively charged electron would have; that is to say, it would move in the opposite direction to ordinary electrons, just as a bubble in water moves against the direction of gravity. Therefore, every time we succeed, by supplying energy, in raising an electron from a state with negative energy up to a state with positive energy, there will thereby be created a *particle couple*,

consisting of a negatively charged and a positively charged electron with the same weights.

Conversely, the presence of a hole in the field of negative energy—that is, the presence of a positively charged electron—would bring with it the possibility of the transition of an electron from the field of positive energy to the hole, when we should have to expect that an energy-quantum would be set free, which would make itself known as electro-magnetic radiation, just as Roentgen radiation arises when one of the inner electrons in an atom has been removed and an outer electron falls into its place. In the process by which the hole is filled in a negative and a positive electron would therefore seem to disappear.

These remarkable consequences of Dirac's theory were received with extreme scepticism by the physicists, partly on account of the somewhat fantastic conception of a space filled up with an infinitude of "donkey electrons," whose presence it was impossible to perceive, but above all because electrons with a positive charge had never at any time been observed.

While in all earlier theoretical concepts of the structure of matter the number of material particles in existence had been deemed constant, according to this theory material particles could under certain circumstances be annihilated, electro-magnetic radiation being thereby set up, or conversely, they could be created, electro-magnetic radiation-energy at the same time disappearing. According to this theory it is possible to forecast how often and under what circumstances such a process of creation or annihilation will come about, and also to calculate the amount of energy which disappears or comes into being in these processes. The frequency of such transformations is found to be extremely small, and the quantity of energy transposed to be very great, being at least 1·1 million electron-volts. Both these circumstances naturally make an experimental confirmation of these processes very difficult.

As a matter of fact Einstein had already shown, in his celebrated theory of relativity, that any quantity of matter with mass m contains a determinate quantity of energy E, given by the expression $E = m \times c^2$, where c is the velocity of the propagation of light; but his theory did not say anything as to the possibility of setting this energy free. Since Dirac's theory was in fact so formulated as to take the theory of relativity into account, the above-mentioned minimum energy of 1·1 million electron-volts is no more than what we find from the above expression by substituting for m the total mass of the Particle Couple: that is, twice the mass of the electron.

The fantastic predictions contained in Dirac's theory were a few years later (1932) confirmed by the discovery of what is known as the *positron*, which was found to have all the properties required by the theory. This discovery, which is a beautiful example of the complementary nature of theoretical and experimental physics, we shall examine more narrowly in a later chapter.

The epoch in physics which we have dealt with in this chapter has been marked by its comprehension of a great many experimental data, which were successfully marshalled under common points of view, thereby leading to a far-reaching understanding of the structure of the atoms. But it was, so to speak, only the outwork of the atoms that had fallen, since the experimental and the theoretical efforts alike had been mainly directed to the outer electronic system of the atoms and the chemical properties bound up with it. Our knowledge of the structure of this electronic system, and of the new laws that hold good for the motions of the electrons in the atoms, had thereby reached a very high degree of perfection, finding its way, as it did, right in among the "innermost" electrons in the atoms. But as for what lay within these electrons—the atomic nucleus, as it is called—this was still, for the most part, an unexplored field.

III

The Riddle of the Nuclei of the Atoms
The Epoch of the New Discoveries

In these last few years we have lived through a period which in respect of great discoveries is in no wise behind the golden age of the great discoveries made about the beginning of the century. This has led to the development of a quite new department of Physics—Atomic Nucleus Physics—which in a few years has so greatly expanded our knowledge of the atomic nuclei that it is already possible to give a fairly complete description of their properties, even though we must naturally always be ready for fresh surprises.

THE ISOTOPES

Among all the manifold physical and chemical properties of the elements there are only two that must be assumed to have their origin directly in the nuclei of the atoms—namely, the weight of the substances and their radio-active properties. We will begin with the weight.

Besides the methods employed by chemistry for determining the proportion between the weights of the atoms of the elements, there is also a physical method for determining the atomic weights, by a process of direct weighing against magnetic and electric forces (see page 41). This method, originally Thomson's, was elaborated into a method of precision by Aston in England, who in 1919 and the following years was working with an apparatus called by him a Mass Spectrograph, a photograph of which is seen in Fig. 24, Plate IV, page 79. In this apparatus, by means of electrical discharges of different kinds, positively charged ions are

produced from the substance which it is wished to examine These ions are now sent through a vacuum, past electrically-charged deflection-electrodes, and in between the poles of an electro-magnet, whereby the ions are deflected from their straight path, the deflection being smaller in proportion to the weight of the ions By the proper choice of potential for the deflection-electrodes and of intensity for the magnetic field Aston succeeded in bringing all the ions with the same weight to a focus after deflection, so that a sharp spot was produced on a suitably placed photographic plate By means of these spots the amount of the deflections could now be measured, after which it was possible, the deflecting electric and magnetic forces being exactly known, to find the weight of the ions and so of the atoms

The first substance that Aston dealt with in his mass spectrograph was the noble gas neon, whose atomic weight had been found by other methods to be 20 2 in proportion to that of hydrogen For this gas J J Thomson had already, with his simpler apparatus, found two different deflections, corresponding to the atomic weights 20 and 22, and Aston now likewise found two sharp spots, corresponding to the weights 20 0 and 22 0, and not, as one would expect, a spot corresponding to 20 2 This was a highly remarkable observation, for it showed that the neon atoms had not all, as hitherto presumed, the same atomic weight but that the gas neon was made up of two kinds of neon atoms with the weights 20 0 and 22 0 The photographs even allowed the quantitative relation between the two kinds of neon atoms to be determined from the degree of blackening in the spots, and there were found to be about 10 times as many atoms with weight 20 as there were with weight 22 The method hitherto used for determining the atomic weight of neon, which gave the result 20 2, consisted only in dividing the weight of a given quantity of neon by the number of neon atoms, which had already been ascertained by other means

Such a method will, of course, give only the mean value for the atomic weights. If now we calculate the mean value by means of Aston's result, we have $(20 \times 10) + (22 \times 1)$ divided by $10 + 1$, which gives approximately $20 \cdot 2$.

Aston now examined a whole set of other substances and obtained similar results: for example, with the gas chlorine, whose atomic weight had been found by the chemists to be $35 \cdot 47$, he discovered the presence of two kinds of chlorine atoms with the atomic weights $35 \cdot 0$ and $37 \cdot 0$, which occurred in the quantitative relation 3 : 1, which again gives us the right mean value, since $[(35 \times 3) + (37 \times 1)] : (3 + 1) = 35 \cdot 5$. It might now perhaps be asked why these differences in the atoms of a substance had not been detected in some other way. The answer is easily given, for we now know that the atomic weight is a property of the nucleus, while all other properties are determined by the number of electrons (the atomic number), which for a given element is one and the same for all atoms, as is found, for instance, from the Roentgen spectra. By Aston's discoveries, therefore, it was established that atoms exist with quite identical physical and chemical properties, but having a slightly differing atomic weight. Such elemental atoms must therefore be brought into the periodic system of the elements at those places which correspond to the atomic number, independently of the atomic weight; and this circumstance has led to these substances being called *isotopes* (*iso* = "equal," and *topos* = "place").

What was most interesting about Aston's discovery was, however, the fact that the isotopes were found always to have *integral* atomic weights; that is, the atoms weigh an integral number of times as much as a hydrogen atom. Many years before this it had already been noticed that the atomic weights of the various elements were extraordinarily close to whole numbers, when the atomic weight of hydrogen was taken as unity. For example, nitrogen had the atomic weight

14·0, and oxygen 16·0, but as many other elements had fractional atomic weights (for instance, chlorine, 35·5), there was a general tendency to assume that the whole numbers were accidental. Aston's investigations now showed that substances having integral atomic weights contained, as a rule, only one isotope, and so the main result of his investigations may be said to be the discovery that all atomic nuclei weigh an integral number of times as much as a hydrogen nucleus, since the infinitestimal weight of the electrons can be neglected.

It was now very natural to suppose that all atomic nuclei were built up of an integral number of particles having the same weight as the hydrogen nucleus; but it must not be at once concluded that the neon nucleus—let us say—(weight 20) contains 20 hydrogen nuclei, for this would mean that it must have 20 positive charges, whereas experience shows that the nuclear charge for neon is only 10. For a time, therefore, it was thought that the nucleus must also contain electrons in such quantity that part of the charge of the hydrogen nuclei was neutralized, as the electrons, owing to their small weight, would not make any perceptible addition to the atomic weight. But this view has been abandoned of late, since other and better possible explanations have been found.

Practically all the elements have now been investigated by the mass spectrograph, so that we have a very precise knowledge of the quantitive relations of the different isotopes for all substances. The ninety or so known elements have been found to consist of altogether some two hundred and fifty different isotopes, some of which, however, occur only in extremely small quantities. For a full characterization of a given atom it is therefore no longer enough to state the atomic number, but we must also state which isotope we are dealing with. It has therefore become the usual thing in physical literature to write both the atomic number and the

atomic weight whenever we speak of a given isotope, these numbers being added below and above respectively to the left of the name or the chemical symbol of the element; as, for example: $^{20}_{10}$Neon, $^{22}_{10}$Neon or $^{35}_{17}$Cl, $^{37}_{17}$Cl. As a good example of a mass spectrogram we have in Fig. 25, Plate IV, page 79, a photographic spectrogram of zinc, which consists of the isotopes 64, 66, 67, 68 and 70, and where the four isotopes with an even-numbered atomic weight are seen to lie at the same distance from one another, while the odd-numbered isotope 67 lies half-way between 66 and 68.

A particular interest attaches to the *heavy hydrogen isotope*, which was found in America in 1932, by Urey and his fellow-workers. The mass spectroscope had never shown anything that pointed to the existence of several hydrogen isotopes, but there was some idea that they must exist, even though in very small numbers. Urey tried by an optical spectroscopic method to track down a heavy hydrogen isotope, for it was to be expected, owing to the greater mass of the nucleus, that the spectrum lines for this isotope must be slightly displaced as compared with the ordinary hydrogen lines. Such a displacement of spectrum lines had, indeed, been found already (see page 82) in the spectrum of the helium ion, while Bohr's theory for the Rydberg constant was able to explain this displacement of spectrum lines as an effect of the great weight of the helium nucleus. By applying Bohr's formula Urey was now able to give an exact forecast of the displacement of the spectrum lines which a hydrogen isotope with mass 2 would produce; and he then tried to photograph the spectrum of ordinary hydrogen by exposing the plate so long that even an infinitesimally small content of heavy hydrogen would make itself known. With an exposure about four thousand times as long as that which was required to bring out the strongest lines in the Balmer series, weak spectrum lines were actually found on the plate, with exactly the wave-lengths which had been forecast.

From this Urey concluded that ordinary hydrogen, besides the ordinary hydrogen atoms of atomic weight 1, contains also hydrogen atoms of atomic weight 2, but only in the ratio 1 : 4,000. In Fig. 26, Plate IV, page 79, we see one of Urey's original photographs. In accordance with the method just described, the heavy hydrogen isotope is written $^{2}_{1}H$, while the ordinary isotope is denoted by $^{1}_{1}H$.

While the isotopes of the heavier elements are characterized by the fact that the difference between the atomic weights of the various isotopes is small in comparison with the atomic weight itself, the relation is quite otherwise in the case of hydrogen, where the heavy isotope weighs twice as much as the light one. Although both these hydrogen atoms have the same number of electrons revolving round the nucleus—that is to say, one electron—we should expect to find a clear distinction in the physical and chemical properties of the two hydrogen isotopes, and for this reason efforts were soon directed towards separating the isotopes from each other. It seemed possible that they might be separated by evaporation, as owing to the great difference between the weights of the isotopes, light atoms would be evaporated first. This was the method employed by Urey, who evaporated a considerable quantity of liquid hydrogen, leaving only a small residue, which was then found to contain the heavy hydrogen in greater concentration. The method, however, was not very practical, so that it was a great advance when a method of *electrolysis* was devised.

According to the theory developed by Arrhenius in Sweden relating to the passage of an electric current through aqueous solutions of various chemical compounds, the current is carried between the submerged electrodes by electrically charged ions, which are produced by the splitting up (disassociation) of the molecules when the substance is dissolved in water. On the electrolysis of an aqueous solution of an acid what usually happens is that the hydrogen ions give up their charge at the cathode and bubble up as ordinary hydrogen. Since the rate at which

the ions move has been found by experiment to be greatest for the light ions, we must expect that in electrolysis the light hydrogen atoms will be the first to disappear. And it was found, when the hydrogen content of old accumulator acid was examined, through which the current had been passing for a long time, that this acid contained heavy hydrogen in a fairly concentrated form.

Following this method, there has been initiated quite recently a technical production of heavy hydrogen, which is carried on more especially in Norway. In that country the *Norsk Hydro*, which has great amounts of electrical energy at its disposal, produces great quantities of heavy hydrogen in the form of water, whose water-molecules contain each two heavy hydrogen atoms.

As was to be expected, this "heavy water," as it is called, shows certain deviations from the properties of ordinary water: for instance, it freezes at 3·8° C. and does not boil before 101·4° C., while its specific gravity is 1·1. The discovery of heavy hydrogen and heavy water is one of the most important practical results that the new atomic physics has to show, since these substances are naturally of the greatest interest for the chemist. It must further be mentioned that heavy water has proved of value in biological research; for example, it enables us to ascertain how quickly water is taken up by and distributed in living organisms. If such an organism is made to imbibe heavy water, this can easily be followed up in the various tissues and organs, as it can easily be distinguished from the ordinary water already contained in the organism.

If now we turn to the task of distinguishing the isotopes of other substances, we find a far more difficult state of things, for the isotopes of a substance do not generally differ very greatly in atomic weight. We must therefore resort to methods which are sensitive to a very slight difference in atomic weight. The difference in atomic weight becomes apparent not only in evaporation and electrolysis, but also when

gases diffuse through porous substances, for lighter atoms will ooze through quicker than the heavier ones. G. Hertz in Germany has made use of this principle, and among other things has completely separated the two isotopes of neon. Finally, it must be mentioned that in various physical laboratories throughout the world work is being done to-day in the direction of using Aston's mass spectrograph on a larger scale, in order to separate isotopes in quantities that can be weighed. Already, in the most favourable cases, pure isotopes have been successfully obtained to the amount of about 1 milligramme in 24 hours.

The reader will perhaps have noticed that through the discovery of the isotopes it has been possible to find a place in the periodic system for the many different *radio-active* substances existing in the radio-active families. Every place in the periodical system has now shown that it can contain several isotopes, or, in other words, the drawers in the card-index to the elements have shown themselves to be roomier than was at first supposed. To see how, for example, the members of the radium family can be brought into the periodical system, we will once again set down the whole genealogical table, adding now both the atomic number and the atomic weight, so as to characterize the different isotopes, as shown in Fig. 27. The α- and β-particles have likewise been given numbers above and below, so that an α-particle, which is a helium nucleus with weight 4 and charge 2, is denoted by ${}^{4}_{2}\mathrm{He}$, and a β-particle, which is an electron with infinitesimally small weight and a negative charge, is denoted by ${}^{0}_{-1}\mathrm{e}$. The correctness of each single step in the transformation series can now be easily checked, since it must be true for each substance that its weight and charge are found from those of the mother-substance by subtracting the weight and charge of the emitted particle; only we must remember that in subtracting the negative charge of the electron we really get an increase of 1 in the nuclear charge.

As we see, there appear in the series two substances $n^0_=83$, so that both must be isotopes of the element bismuth. These isotopes differentiated from each other and from ordinary bismuth partly by their differing radio-active properties (radiation and length of life), and partly by their atomic weights, which are respectively 214 and 210, while the atomic weight for ordinary bismuth is 209. Further, there are three lead isotopes, $n^0_=82$, with atomic weights 214, 210, and 206, of which the last is the end-product of the trans-

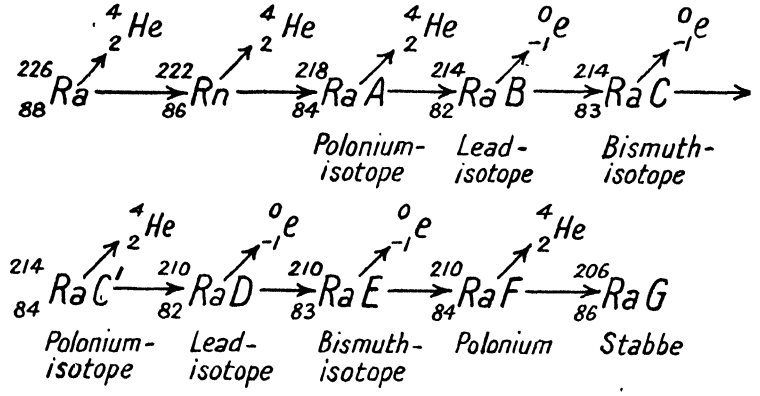


FIG. 27

formation series, not being itself radio-active. Altogether there are emitted from the members of the radium family 5 α-particles and 4 β-particles before a radium atom has been transformed into a stable lead atom.

Besides the radium family two other radio-active families are known, namely, the actinium family and the thorium family, whose affinity has been fully elucidated, and both of which have, as end-product, a stable lead isotope. These three end-products have the atomic weights 206, 207, and 208, which are the very isotopes which we find by means of the mass spectroscope occurring naturally in ordinary lead.

We have now brought that order into the last drawers of

the card-index to the elements which we promised above. It must be added that Soddy in England had as early as 1910 assumed the existence of isotopes for the radio-active substances, so as to bring these into the periodic system.

While formerly ninety different kinds of atom were known—that is, exactly as many as the number of elements—we now, after the discovery of the isotopes, know exactly as many different atomic nuclei as there are isotopes: that is to say, about two hundred and fifty for the stable elements, to which must be added about fifty for the radio-active substances.

THE ARTIFICIAL TRANSMUTATION OF ELEMENTS

As has already been said, the discovery of the isotopes led to the conjecture that all atomic nuclei were built up of a great number of small particles with the same weight as the hydrogen nucleus; but no further information could be obtained along this path. Radio-activity made it perfectly certain that corpuscles were emitted from the nuclei in the form of α- and β-particles, but this was not enough to show how the nucleus was built up. The best method would of course be to find some means of disrupting the atomic nuclei, so that the several building-stones could be examined. Now this was not such an easy thing to do, firstly, because the atomic nuclei, on account of their smallness, are difficult to hit, and secondly, because the blows would have to be heavy ones.

Through Rutherford's celebrated demonstration of the existence of the atomic nucleus (page 65 ff.) by bombarding atoms with α-particles, the immeasurably small dimensions of the atomic nucleus were established by the very infrequency with which the nucleus could be hit. And when it comes to calculating the energy which we must assume to be necessary in order to make a hole in an atomic nucleus, we must ask the reader to remember that the further we go into the atom on which we wish to act, the greater is the energy that

must be applied. In order to knock away an outer electron from an atom, it is enough, as we have learned from Bohr's atomic theory and Franck and Hertz's experiment, to apply an energy of about 10 electron-volts. If, on the other hand, we have to do with the innermost electrons in an atom, the electrons which have to be acted upon in order to produce Roentgen radiation, we have to apply from 10,000 to 100,000 volts. Finally, closer investigation will show that the energy needed in order to act upon an atomic nucleus is an energy of several million electron-volts. To get a clear notion of these conditions we will consider a little more narrowly the amount of energy in the radiation of the radio-active substances.

As to the α- and the β-rays, magnetic and electric deflection experiments have not only disclosed their nature, but they have also yielded important information as to the energy and velocity of the α- and β-particles. The velocities found for the α-particles lie between 14,000 and 20,000 kilometres a second, which corresponds to kinetic energies of between four and eight million electron-volts. For the β-particles we find a very much higher velocity, that is, one approaching the 300,000 kilometres a second of the velocity of light, but the corresponding kinetic energy, owing to the far smaller mass of the electron, is "only" two to three million electron-volts at the most.

When, in practice, we wish to measure the energy of α-particles, we now always proceed by measuring their range in air, since in the course of time so many deflection experiments have been made that we know exactly how far α-particles with any given kinetic energy can travel in air. For example, α-particles from RaF have a range of $3 \cdot 8$ cm. and energy $5 \cdot 3$ million electron-volts, while α-particles from RaC* have a range of $6 \cdot 9$ cm., which corresponds to $7 \cdot 7$ million electron-volts.

From the γ-rays also we can obtain similar information

* Fig. 1, p. 29.

as to the energy-conditions in the radio-active atomic nuclei. The γ-rays are not of a material nature, but have been shown to be an extraordinarily short-waved electro-magnetic radiation which accompanies the emission of material particles, but which does not in itself give rise to any atomic transformation. By means of interference in crystals it has been possible, as with Roentgen rays, to measure the wave-length for some of the γ-rays. This method, however, is of no use for waves shorter than about $0 \cdot 03$ Å, so that we have to employ more indirect methods for determining the wave-length.

One of these consists in causing the γ-rays to produce a photo-electric effect (cp. page 59), whereby electrons are set free which have taken up the γ-rays' energy, which we can thus measure. Since this energy, according to Einstein's explanation of the photo-electric effect, is transformed into quanta whose amount is Planck's constant multiplied by the oscillation-number, it is a simple matter to calculate the wave-length from this. By such methods a whole γ-ray spectroscopy has been elaborated, the several "spectrum lines" for the various radio-active substances having been measured.

Wave-lengths have been measured as low as $0 \cdot 004$ Å, which corresponds to energy-quanta of three million electron-volts. If the nuclei of the radio-active substances are capable of sending out quanta with such amounts of energy, then they must under certain conditions be holding energies of these magnitudes.

All three kinds of radiations from the radio-active substances show us what vast amounts of energy reside in the atomic nuclei—or at all events in the nuclei of the radio-active substances. In the same way we have also obtained a notion of what quantities of energy must be brought into play in order to split up the atomic nuclei by artificial means. It therefore seems a very obvious matter to employ the radiation from the radio-active substances for bombard-

ing the atomic nuclei of other substances. But it is found that the β-particles cannot be utilized, since owing to their small weight they are much too easily deflected by the electric forces in the atom, even with energies of several million volts. On the other hand, the heavy α-particles have a great striking force, even if their energies are not essentially greater than those of the β-particles.

Once more it was Rutherford who took the decisive step, when for the first time he succeeded in effecting an artificial splitting of the atom in 1919, by using the α-particles as projectiles. Rutherford sent his beloved α-particles into a container filled with nitrogen under pressure of one atmosphere, which had been carefully dried so as to be freed from every trace of hydrogen. By means of a zinc sulphide screen he now measured the range of the α-rays, which for the preparation used was about 7 cm. But if he now put the α-ray preparation at a greater distance from the screen, he still could see flashes now and again, and these flashes could be followed right up to a distance of 40–50 cm. This could only be understood as meaning that the nitrogen nuclei, during the bombardment with α-particles, had sent forth new particles with a range much greater than that of the α-particles themselves. A thoroughgoing inquiry into the nature of these long-range particles, for example, by deflection in electric and magnetic fields, showed with certainty that they were nothing but hydrogen nuclei, which could only come from the nitrogen; so that it became extremely probable that nitrogen nuclei contain hydrogen nuclei as structural material. This discovery of the fundamental importance of the hydrogen nucleus led to the adoption of a special name for it, and it was called a *proton.*

Rutherford's first experiment of splitting the atom was quickly followed by many similar experiments with various lighter substances, of which several were found, like nitrogen, to send out protons. As a fascinating illustration of Ruther-

ford's experiment Blackett succeeded in taking cloud-chamber photographs of the process of nuclear dissociation, photographing the paths of the α-particles in a Wilson chamber filled with nitrogen. Owing to the extreme infrequency with which the α-particles effect a splitting of the nucleus, he had to photograph many thousands of paths before he could get a picture showing the emission of the proton. Fig. 28, Plate V, page 148, shows one of the best photographs, where in a sheaf of many α-particles we see one which shows a branching track where the collision between the α-particle and the nitrogen nucleus has occurred. The thin straight path across the field is the swift proton, which is distinguished by showing less ionization along its path than occurs along the track of the bombarding α-particle. The short branch is the path of the atomic nucleus, which is set in motion by the collision. On the other hand, there is no branch corresponding with the track of the α-particle after the collision, from which we may conclude that this particle was taken into the nitrogen nucleus when the proton was cast out. As all Blackett's photographs of the collisions showed exactly the same characteristics, we must conclude that the process was that expressed in the following equation, which on the left shows the atomic nuclei before the collision, while on the right of the sign of equality are the nuclei formed during the process:

$$^{14}_{7}N + ^{4}_{2}\mathrm{He} = ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

Since the sum of the atomic numbers below the line must be the same on each side of the equality sign, as must the sum of the mass numbers standing above it, there must be formed during the process an element with atomic number 8; that is to say, an oxygen isotope with atomic weight 17. It is interesting to know that this oxygen isotope was not found until several years later, existing in exceedingly small quantities in ordinary oxygen.

By Rutherford's experiment, therefore, we were given not only the information that the atomic nuclei contains protons, but also, for the first time in the history of mankind, the proof that it was possible by human intervention to transform one element into another, though only in infinitesimal quantities. To be sure it was only the atomic nucleus that was transmuted from nitrogen into oxygen, but this, after all, was the most important thing, for the rest of the process continues of itself, as the newly-formed oxygen nucleus, immediately it has come to rest, will instantly capture those electrons which it needs to make up its full number. We can say without exaggeration that with this experiment a new era was heralded for physics, while a wholly new field of research was opened up: the experimental physics of the atomic nucleus.

EXPLODING THE NUCLEUS WITH ARTIFICIAL PROJECTILES

Even though the α-particles from the radio-active substances may have energies as great as 6–8 million electron-volts, there is a limit to the number of nuclear transformations that can be obtained by this means, for we have only a limited number of particles at our disposal. A strongly radio-active preparation can, it is true, send forth 10^9 α-particles to the second, but since as a rule we can only reckon on getting one "bull's eye" for every 10^6 α-particles, we can at best succeed in transforming only about 1,000 atoms a second. To transform the whole of one gramme of matter, which contains somewhere about 10^{22} atoms, we should therefore have to keep up the bombardment for 10^{19} seconds, or about a billion years, which would hardly be a profitable business.

If on the other hand, we could cause particles to travel fast enough—α-particles or protons—by some artificial device, as, for instance, by means of a positive-ray tube, in which ordinary helium ions or hydrogen ions, which can be obtained in unlimited quantities, are accelerated by very

high electric potentials, we could secure a much greater yield. If, for example, we could produce a proton ray with a current of no more than one milliampère, which is about $\frac{1}{50}$ of the current flowing in an ordinary incandescent lamp, the ray would carry about 10^{16} particles a second, which would be millions of times as many as from the strongest radio-active preparations. The difficulty, however, is to obtain such high electric potentials that the energy of the protons becomes great enough.

At the time when Rutherford was performing the first successful experiment in splitting the nucleus, there were high potential apparatuses which could give a uniform potential of some 200,000 volts, but this was regarded as much too small for splitting the nuclei when compared with the α-particles' millions of volts. But as technology advanced, rather higher potentials were reached, and in 1932 two of Rutherford's pupils, Cockcroft and Walton, were bold enough to make the trial with a home-made high-tension apparatus capable of yielding potentials up to 700,000 volts. Their boldness was rewarded beyond all expectations, for they succeeded in producing nuclear explosions with only a few hundred thousand volts.

Cockcroft and Walton sent a stream of protons, produced as canal rays, into a long tube, where they were accelerated by a potential of some hundreds of thousands of volts; they then made these swiftly-moving protons strike a small sheet of the metal lithium. They found that from this sheet there were emitted particles with a very high velocity, which on closer examination revealed themselves as helium nuclei, or, in other words, *artificial α-particles*. As it was known for certain that there were no radio-active substances in the apparatus, nor any helium either, since the experimentors were working only with hydrogen and lithium, the only possible assumption was that they were in the presence of an elemental transformation, which here had been effected for the first time in

a wholly artificial way. Since the most frequently found isotope in ordinary lithium has the atomic weight 7, it was assumed that it was a lithium nucleus of this kind that took up a proton, whereby the nucleus was split up into two helium nuclei, in accordance with the following equation:

$$^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} = {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

Remark again that both the sum of the mass numbers and the sum of the atomic numbers are the same before and after the process.

While Cockcroft and Walton made use of a zinc sulphide screen for observing and measuring the α-particles that were formed, shortly afterwards the paths of the α-particles were successfully photographed by means of a cloud-chamber. Fig. 29, Plate V, page 148, shows one of these photographs, in which the protons have entered from above, while the bombarded lithium is in a tube, which lies at the bottom in the cloud-chamber. The photograph shows clearly that the two α-particles formed at each splitting of the nucleus are thrown off in pairs, in very nearly opposite directions, and with fully determinate ranges. These artificial α-particles were found on being exactly measured to have a range in air of 8·4 cm., which is greater than that of the swiftest natural α-particles from radio-active substances. This range corresponds to an energy of altogether 17 million volts for the two particles, which may strike us, indeed, as amazing, seeing that only protons with an energy corresponding to about 400,000 volts were used. This evidently is an instance of the liberation of the great quantities of energy that are bound up in the atomic nuclei.

It was found that the explanation of the great increase in energy lay in the fact that a part of the mass of the original nucleus had disappeared and had been converted into the kinetic energy of the α-particles. As will perhaps be remembered, Einstein's theory of relativity (see page 119) brought

with it the remarkable consequence that to a given mass there corresponds an amount of energy which is equal to the product of the mass and the square of the velocity of light, although it had not then been proved by any experiment that mass could be converted into energy or conversely. If this conversion should be the explanation of the energy developed in the lithium experiment, it was to be expected that the sum of the atomic weights for the atoms in question would be slightly diminished in the process.

The measurements of the atomic weights by Aston's mass spectrograph, as described above, had certainly yielded the result that the atomic weights of all isotopes were an integral multiple of hydrogen's. But as measurements grew more exact it was found that there were small deviations from this rule. We have already said in the Introduction that an oxygen atom weighs about sixteen times as much as a hydrogen atom, but actually the precise number is 15·86. However, since long ago it was agreed on practical grounds to take the atomic weight of oxygen as exactly 16, hydrogen, which is 15·86 times lighter, is given the atomic weight 1·008. For the lithium isotope $^{7}_{3}$Li we thus find the weight 7·017, while the atomic weight of helium becomes 4·003. The fundamental explanation of these small discrepancies in the atomic weights must be postponed until a later section (page 172). Here we shall merely employ these values to account for the mighty lithium explosion.

As regards this experiment, by adding the atomic weights of hydrogen and lithium we obtain the value 8·025, which gives the total mass before the experiment, while the total weight of the two helium nuclei that were produced in the course of the experiment is only 8·006. The difference between the mass of the particles before and after the experiment is therefore 0·019, which when converted into grammes gives 3×10^{-26}g. If this loss in mass is now substituted in Einstein's equation for the energy of each mass, we obtain an energy of

about 17 million electron-volts; and this is in the closest agreement with the kinetic energy for the α-particles as measured in the experiments, for we can neglect the kinetic energy of the incoming protons, which was small in comparison with the 17 millions.

Cockcroft and Walton's experiment was thus in many regards a pioneer achievement: partly because it was the first time that a wholly "artificial" transmutation of an element had been successfully produced, and partly because the record hitherto held by the α-radiation from the radioactive substances had been beaten, and this, be it remembered, by using protons with only a relatively small energy. And lastly, these experiments gave an experimental confirmation of the connection between energy and mass which Einstein had found by purely theoretical considerations.

When research of this kind has once been effected, it is always a comparatively easy matter to carry the experiments further; and a whole series of successful experiments of nuclear splitting were soon performed with various substances. Further; the idea was conceived of using the nucleus of the heavy hydrogen isotope as a projectile, as soon as heavy hydrogen had been successfully produced in sufficient quantities. Since, as time went on, this atomic nucleus was found to be particularly useful in nuclear processes, it was honoured, like the ordinary hydrogen nucleus, with a special name: it is now known as a *deuteron.*

As an example of what deuterons can do we will only mention the bombardment of lithium, by which the lighter lithium isotope ${}^{6}_{3}\mathrm{Li}$ is split into two α-particles, in accordance with the equation: ${}^{6}_{3}\mathrm{Li} + {}^{2}_{1}\mathrm{H} = {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$, the α-particles being emitted with a total energy of not less than 23 million electron-volts. The proof that it was actually this said isotope of lithium which entered into the process was given by Oliphant in England in 1934: he made use of lithium preparations in which the two isotopes with weights 6 and

7, which are found in naturally occurring lithium, had been separated by an apparatus on the principle of Aston's mass spectrograph.

THE NEW ELEMENTARY PARTICLES

Before we go on to describe the sweeping developments that followed the first cases of atomic splitting, we must first of all deal with the discovery of certain small particles which had hitherto evaded pursuit by the physicists. These new particles belong to the distinguished group of minute bodies which bear the name of *elementary particles*, for they are assumed to be simple in contrast to such minute bodies as atoms and atomic nuclei, which again are built up of these elementary particles.

Up to 1932 we had known only of the existence of two such elementary particles, namely the *electrons*, forming the outer shell of the atoms, and the *protons*, which were a constituent of all atomic nuclei. In that year 1932, so eventful for physics, no less than two new elementary particles were introduced to us, namely the *positron*, found by Anderson in America, and the *neutron*, found by Chadwick in England.

The existence of positrons, that is, of particles with the same weight as the electrons, but with a positive elementary charge, had already been forecast (page 118) by Dirac on purely theoretical grounds, which, however, not many physicists had accepted. Anderson's discovery of this particle might be called a lucky find, for the positron was the last thing of which he was thinking when he found it. What Anderson was working on was quite another branch of physics, but one just as enthralling; namely, the investigation of what are known as the *cosmic rays*. This mysterious natural phenomenon, which was first discovered by V. F. Hess in Austria in 1912, manifests itself as a radiation with immense powers of penetration, which incessantly, day and night, year after year, falls from space onto the Earth. The dis-

covery of the rays was due to their making the air a conductor for electricity, ionizing it in the same way as the rays from the radio-active substances and the Roentgen rays. Their penetrative powers were so great that they could still be observed after they had passed through iron or lead plates a metre in thickness. That the rays do really come from space is seen from the fact that their power increases very greatly as we rise in the earth's atmosphere. V. F. Hess discovered the cosmic rays, in fact, when he was taking measurements from balloons of the ionization of the air.

This mysterious radiation has for years attracted the attention of a great many investigators, who have sought a solution to the enigma along various paths. Among other methods is that of balloon ascents which have been made to very great altitudes, and have aroused interest far beyond the circle of professional physicists. Piccard of Belgium rose to the fantastic height of 16 kilometres, and at this height measured the strength of the radiation. But without wishing to belittle this splendid achievement, we may remind ourselves that the most important results have been reached by sending up balloons with self-registering instruments—a method which was worked out to a high degree of perfection by Regener in Germany, who was able to obtain exact measurements up to a height of 30 kilometres above the earth's surface. At these altitudes the radiation is several hundred times as strong as on the earth's surface, since the earth's atmosphere weakens it as much as ten metres' depth of water, or a lead plate about one metre in thickness. Further investigations have been made as regards the weakening of the rays by deep layers of water or of earth, measurements having been taken by sinking the measuring apparatus into great depths of water or taking it down into mines.

In spite of all these achievements the real nature of the cosmic rays continued for a long while to be quite inexplicable. There was hesitation between two different hypotheses,

one being that the rays were an extraordinarily short-waved electro-magnetic radiation with an even shorter wave-length than the γ-rays, while on the other hypothesis they consisted of electrons with very high velocities. Among the various other methods applied to studying the nature of the cosmic rays, the cloud-chamber method plays an especially important part, since with this direct photographs can be taken of the paths of the radiation's own particles, or of secondary particles which this radiation may discharge when passing through various substances.

It was just such an investigation that Anderson was engaged upon. He put his cloud-chamber between the poles of a strong electro-magnet, so that by the deflection of the paths he would be able to determine the speed of the particles, and then he began to photograph the paths. Most of his photographs showed nothing at all for the cosmic rays, although they are always present, yet fall in so scattered a fashion that on the average any square decimetre is hit only once a second. But some photographs, on the other hand, showed electrons with greatly varying velocities, which arose from the greater or lesser curvature of their paths, and lastly a very few photographs were obtained showing paths whose curvature was in the opposite direction to that of the electron-tracks, so that the images must have been produced by particles with a *positive* charge.

Fig. 30, Plate V, page 148, shows the historical photograph in which the *positron* came into sight for the first time. The particle has passed through six millimetres of lead sheet which had been introduced into the cloud-chamber, and had been slowed down by it, as is seen from the strongly pronounced curvature in its path, for a slow particle will be more strongly deflected than a fast one. Thanks to the presence of the lead sheet, the direction of the particle's motion could thus be absolutely determined, since the particle, in passing through the lead, can, of course, only *lose* in

velocity. It was the knowledge of the direction of its motion that afforded the possibility of determining beyond a doubt that it, the particle, was a positron, for an electron moving in the opposite direction with the same velocity would describe exactly the same path.

Further, the photograph was able to tell us something about the mass of the new particle. At first sight it might perhaps be thought that the particle was a proton, which is indeed positive; but as the proton is fairly heavy, it must have been unusually slow, since the path was so strongly curved; so slow a proton, however, could not travel more than a few millimetres in air, much less could it make its way through the lead sheet. If, on the other hand, we assume that the particle's mass is the same as the electron's, then we can understand its great penetrative power, since the curvature then answers to a kinetic energy of 63 million volts before and 23 million volts after its passage through the lead sheet.

One photograph would hardly suffice for a full proof of the positron's existence, but very soon many more were successfully obtained. A great improvement in the experiments was made by Blackett and Occhialini, who fitted their apparatus with a "self-release," so that the radiation itself set the cloud-chamber working, and uncovered the photographic lens. This way saved the need of the numerous photographs that showed nothing at all, and so many photographs of positrons were now obtained that their existence had to be regarded as beyond all dispute.

It still remained to show that it was really the particle which Dirac had forecast that we now had before us. Under certain circumstances it should have been possible, so to speak, to create this particle by the transformation of energy into a "couple," consisting of a positron and an electron. The amount of energy needed, which on this theory had to be at least $1 \cdot 1$ million volts, could, for instance, be obtained from a suitably short-waved γ-radiation. Since through the

investigation of the cosmic radiation certainty had now been reached as to the existence of the positron, the wish was felt to bring about this "couple-formation" by artificial methods. In this success was attained about the same time by Anderson in America, Lise Meitner in Germany, and Joliot-Curie, husband and wife, in France. A cloud-chamber was irradiated with γ-rays having an energy of over $1 \cdot 1$ million volts, and photographs were actually obtained showing two such particles, starting from the same point, whose paths were curved by a magnet in opposite directions. Fig. 31, Plate V, page 148, shows such a creative process, which has occurred in the gas in the cloud-chamber, the γ-radiation used having followed the direction shown by the arrow.

In spite of the scepticism which Dirac's theory had encountered, these experiments showed clearly enough that the theory, in its broad outlines, led to the correct results, for the "couple-formation" which he had forecast not only took place, but also showed itself with just that frequency, or rather infrequency, which the theory required. Finally, we may mention that it has also been found by experiments that the reverse process to couple-formation takes place, by which positrons and electrons disappear, while at the same time there are emitted γ-ray quanta with the required energy of $1 \cdot 1$ million volts.

Before we pass on from the wonderful tale of the positron, it is natural to say something about the contribution which Dirac's theory of the positron can make towards the solution of the problem of the nature of the cosmic radiation. It is now assumed that this is, in any case, a mixture of electrons, positrons, and γ-rays, which are in a state of constant interaction: the γ-radiation gives rise to high-velocity electrons and positrons, which in turn are either destroyed by the renewed emission of γ-rays, or else, merely by being slowed down, they send forth short-waved electro-magnetic radia-

tion, just as the continuous Roentgen radiation is brought about by the slowing down of high-velocity electrons.

But there are still many unsolved problems relating to the cosmic rays; as, for instance, their origin in space, or the question of their possible biological effects. It is a field in which we must be ready for many surprises, especially by reason of the vast energies which are converted in the processes of which we have spoken, and which in certain cases amount to fully 1,000 million volts. Here we are in a sphere which lies far outside anything which we can hope to realize by laboratory experiments, and in which there are consequently undreamed-of possibilities of absolutely new discoveries.*

The reader with a feeling for symmetry might now perhaps expect that the next new elementary particle should be a "negative" proton; but unhappily we have to disappoint such a reader with the news that this particle, if it does exist at all, is still waiting to be found. The next new elementary particle was undoubtedly found to have the same mass as the proton, but on the other hand it had neither a positive nor a negative charge. Its discovery made greater difficulties than that of the positron, since a neutral particle cannot make paths in a cloud-chamber. For since it has no electrical charge, there is no electric attraction or repulsion between it and the electrons in an atom, so that it is hard for it to form those ions in the air which are the condition for the visible tracing of paths in the cloud-chamber.

After it had been found, in Rutherford's first experiment in splitting the nucleus, that there were many lighter atomic nuclei which could give off protons when they were bombarded with α-particles, there were many research workers

* Quite lately it has been discovered from cloud-chamber photographs that there sometimes appears in the cosmic radiation a wholly new particle, the *meson* or *mesotron*, whose mass lies between the proton's and the electron's, but whose properties are not yet fully known.

who continued to perform similar experiments. It was then found that when the substance beryllium was bombarded with α-particles, it emitted, instead of protons, a penetrating γ-radiation, and, what was still more remarkable, a wholly new kind of radiation, which was likewise highly penetrative, and which was distinguished by its highly peculiar properties. While all the earlier known kinds of ray could be detected through their ionizing power, this was not the case with the new radiation, so that this again could not trace any paths in a cloud-chamber. On the other hand, this radiation, known as *beryllium radiation*, had the power, when passed through various lighter substances, of giving the atomic nuclei of the substances such violent thrusts that they traced paths in a cloud-chamber several centimetres in length. So powerful a thrust against the heavy atomic nuclei could not, however, be given by a light particle, just as a heavy-weight boxer cannot easily be knocked out by a light-weight. On measuring the length of the paths traced by the atomic nuclei for various substances after impact, it was, moreover, possible to determine to which weight-class the propelling particle belonged. Chadwick was the first to do this: by measuring the range of hydrogen nuclei and nitrogen nuclei set moving by the beryllium radiation, he found that the radiation was made up of particles with very nearly the same mass as the proton. Since these new particles, as we have already said, did not themselves trace out paths in a cloud-chamber, they were necessarily electrically neutral, and therefore Chadwick gave them the name of *neutrons*.

In Fig. 32, Plate VI, page 149, there is a photograph of a cloud-chamber filled with helium, where outside the chamber there had been placed what is known as a "neutron source," that is to say, a blend of beryllium powder and an α-radiating, radio-active preparation. The neutrons coming from this source, which easily make their way through the walls of the chamber, are not seen at all in the photograph.

On the other hand, there is visible a short path traced by a helium nucleus that has been struck by a neutron and thereby set in motion. The fact that the path both starts and ends in the air of the chamber itself shows clearly that the cause of the nucleus's motion, namely, the neutron, is invisible. These photographs made as great an impression on the physicists who saw them for the first time as would be made on the reader if this book, suddenly and without any visible cause, were violently to fly up to the ceiling.

Neutrons on the whole show what is for a material particle the most peculiar behaviour; and this comes from their not being electrically charged. Thus they can travel through several kilometres of air, or can pass through lead sheets 10–20 centimetres in thickness, while a proton with the same velocity would be brought to a standstill by lead a fraction of one millimetre in thickness. For a charged particle, as it passes through matter, will ionize the atoms lying in its path, which, as we have just seen, is the necessary condition for being able to see the path in a cloud-chamber. But each time an atom is ionized the ionizing particle will lose as much kinetic energy as corresponds to the ionization potential for an outer electron in the given atom. As this energy amounts to about ten volts, a proton, for example, with an energy of 1 million volts will have used up its velocity by the time it has formed 10^5 ions; and this it does in a distance of only a few centimetres in air. An uncharged particle, on the contrary, which does not ionize the atoms, cannot lose its energy in this way, but only by colliding with the atomic nuclei themselves, and as such collisions are excessively rare we can understand that neutrons can make their way through great thicknesses of matter without being slowed down. It is, therefore, also impossible to collect neutrons in a container, for even the densest material of which we could make a container will be porous as a sieve for the neutrons.

After the new elementary particle had been discovered

in spite of its tendency to hide, speculations began as to how it actually had come into being. If beryllium, on being bombarded with α-particles, sends out neutrons, we are obviously once more watching a process of nuclear splitting which consists in an emission of neutrons from the nuclei. As beryllium, however, is a solid, we cannot, as, for instance, in Rutherford's explosion of the nitrogen nuclei, make cloud-chamber photographs of single processes, and then study these in detail. But as there is only one beryllium isotope, namely ${}^{9}_{4}\mathrm{Be}$, there are good reasons for assuming that the process by which the neutrons are formed can be expressed by the following equation:

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

where the neutron with mass 1 and charge 0 is shown by the symbol ${}^{1}_{0}\mathrm{n}$. In the process, therefore, is formed the usual isotope of carbon ${}^{12}_{6}\mathrm{C}$. Neutrons are emitted not only by beryllium, but also from a series of other lighter substances, when they are bombarded with α-particles, but the yield is as a rule far smaller.

When the neutron was discovered, all those who had been speculating on the structure of the atomic nuclei breathed a sigh of relief, for now it was seen that we had got hold of that elementary particle which was needed for understanding how the nuclei were built up. Hitherto it had been assumed that nuclei contained as many protons as corresponded with the atomic weight—a necessary assumption if we were to understand why the atomic weights lay near the whole numbers. But by this assumption the nuclear charge was much too great, since this, as a rule, is less than the half of the atomic weight. To neutralize the charge of the surplus protons the notion had accordingly been held that the nucleus contained also the right number of electrons to give the correct nuclear charge, but this assumption had encountered various theoretical difficulties.

One of the greatest of these difficulties was that the electrons in the nucleus, owing to their spin, would presumably give the nucleus magnetic properties, so that this nucleus would exert magnetic action upon the outer electrons of the atom. Such action would find its outlet in an increased splitting up of the spectrum lines of the substance, and this would conflict with the results of experiment, since the usual splitting up of the spectrum lines into multiples could be explained only by the spin of the outer electrons.

This is why the neutron was so welcome: for now, as was first proposed by Heisenberg, we could quite simply think of every atomic nucleus as being built up of as many protons as corresponded with the nuclear charge, together with just so many neutrons that the weight of all the particles together equalled the atomic weight. For instance, the heavy hydrogen nucleus (the deuteron) ${}_1^2\mathrm{H}$ must be made up of 1 proton and 1 neutron, and an α-particle; ${}_2^4\mathrm{He}$ must be made up of 2 protons and 2 neutrons. In the same way, the lithium isotope ${}_3^6\mathrm{Li}$ would have 3 protons and 3 neutrons, and the lithium isotope ${}_3^7\mathrm{Li}$ 3 protons and 4 neutrons, while a radium nucleus ${}_{88}^{226}\mathrm{Ra}$ would contain 88 protons and $226-88 = 138$ neutrons.

That the heavy hydrogen nucleus is really nothing else than an ordinary hydrogen nucleus together with a neutron was directly proved by way of a very pretty experiment, which succeeded in splitting up the heavy hydrogen nucleus into its constituent parts. This was done by irradiating heavy hydrogen with a very short-waved γ-radiation, through which the deuteron was split up into a proton and a neutron, both of which could be shown to be present experimentally. The process, which can be expressed by the equation:

$$ {}_1^2\mathrm{H} = {}_1^1\mathrm{H} + {}_0^1\mathrm{n} $$

is worthy of note in that it is not, like all the other nuclear processes hitherto, effected by shocks communicated by material particles, but by irradiation with electro-magnetic waves, so that it is quite analogous to the above-described

PLATE V

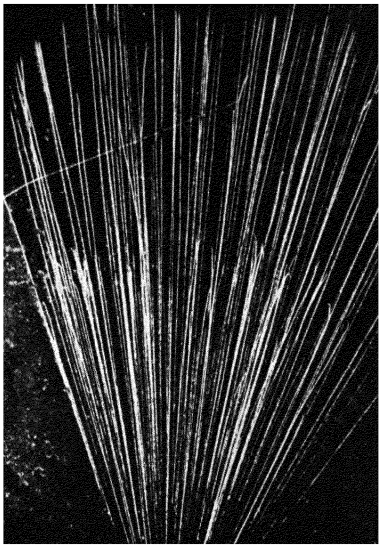


FIG. 28.—Cloud-chamber photograph of an artificial element-transformation, where an α-particle knocks a proton away from a nitrogen nucleus.

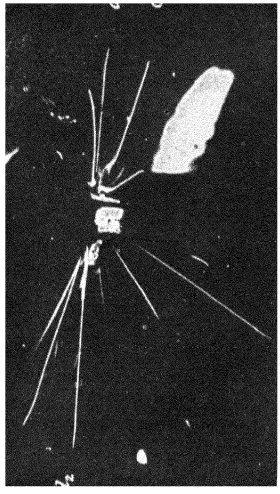


FIG. 29.—Cloud-chamber photograph of the nuclear explosion of lithium. We see the α-particles formed being sent out in couples in opposite directions. See c_1, c_2 and d_1, d_2.

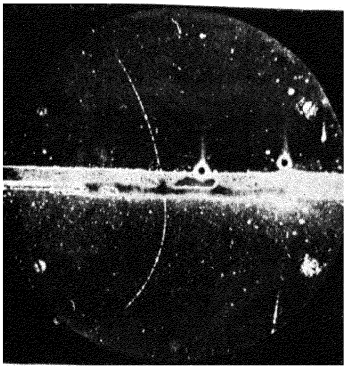


FIG. 30.—The first cloud-chamber photograph of a positron. The bright belt across the photograph is a lead sheet.

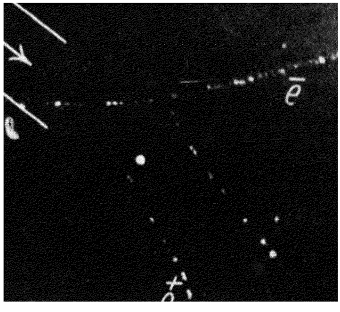


FIG. 31.—Photograph of the paths of a couple, consisting of a positron $\overset{+}{e}$ and an electron e^-, formed in the cloud-chamber by γ-radiation, which is coming in the direction of the arrow between the two sharp lines on the left.

PLATE VI

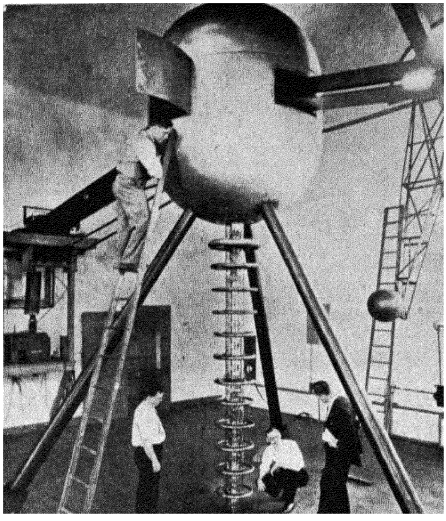


FIG. 34. High-tension apparatus of the van de Graaf type for 1·2 million volts.

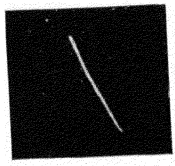


FIG. 32.—Path of a helium nucleus which has been given a thrust by a neutron.

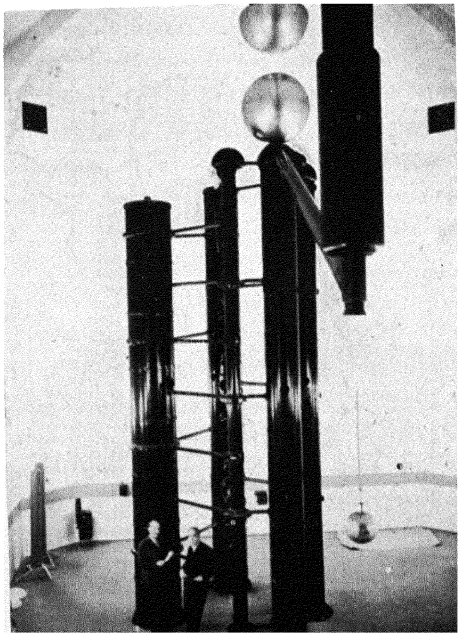


FIG. 33. High-tension apparatus for 1 million volts erected in the University Institute for Theoretical Physics in Copenhagen. At the foot of the apparatus are standing Professor N. Bohr (right) and Professor von Hevesy.

photo-effect upon atoms, where through irradiation with short-waved light an atom may be split into an electron and an ion. There is, however, the distinction that for the *nuclear photo-effect* there is needed an enormously greater energy, for which reason the process can be carried out only by making use of the shortest-waved γ-radiation which we have at our disposal.

But it must not be thought that all the difficulties were solved at one stroke by assuming that the atomic nuclei consisted merely of protons and neutrons. For we know that many of the nuclei of the radio-active substances emit electrons in the form of β-particles, and this fact tends to favour the older view, that there were electrons even in the nuclei. But the difficulties of this view, as discussed above, are so compelling that we are driven to find another explanation for the β-ray emission. Since through Dirac's theory and the experiments described we have shown that it is a fact that electrons can be created or annihilated, it is not perhaps so very fantastic to conceive that the electrons emitted as β-radiation were not previously present in the nuclei, but were formed through a creative process at the moment of emission. As an atomic nucleus in a β-ray emission retains its mass, but has its positive nuclear charge increased by 1, it is reasonable to assume that it is one of the neutrons in the nucleus which, through the β-ray emission, has changed into a proton in the following way:

$$ {}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{0}_{-1}\mathrm{e} $$

The essential point about this new view is, however, that the neutron is not conceived as a composite particle, made up of a proton and an electron, but, on the contrary, as an elementary particle, which in the act of creation whereby the electron is formed is changed into the second elementary particle, the proton.

Since we have now considered all the elementary particles

which have so far been discovered, we will pass on to discuss the new processes of nuclear splitting, in which these particles play a part.

ARTIFICIAL RADIO-ACTIVITY

Until a very few years ago the most important instrument of all in the development of modern atomic physics was undoubtedly to be found in the α-rays. In experimental physics, as a tool in the hands of the right men, these rays have played an essential part in the decisive discoveries as to the structure of the atoms. We will only remind the reader that it was by means of the α-particles that Rutherford showed the existence of the atomic nuclei, and that it was likewise through a bombardment with α-particles that he effected the first artificial splitting of the atom. Further, as we have just seen, the α-particles are able to strike the neutrons away from the atomic nuclei, and thereby they have given us a new elementary particle. Lastly, we shall now hear something of the latest achievement of the α-rays: the production of artificial radio-activity.

In 1934 F. Joliot and his wife Irène Joliot-Curie, a daughter of Madame Curie, began to experiment with the bombardment of aluminium with α-particles. They discovered that the aluminium, besides emitting neutrons, began after a few minutes to send out a strongly ionizing radiation, which continued for some time after the α-ray preparation had been removed. This rise and fall in the radiation suggested that a radio-active substance had been formed whose radiation died down as the substance was transmuted. From cloud-chamber photographs in a magnetic field they saw at once that the radiation was made up of *positrons*.

To reach a closer knowledge of the origin of the radiation they dissolved the irradiated aluminium sheet in hydrochloric acid, whereby hydrogen was developed, which bubbled up through the acid and was collected in a glass tube.

It was then found that the radio-active substance came off with the hydrogen, for the contents of the glass tube also emitted the positron radiation, whose intensity sank to half-value in the same time as the radiation from the aluminium. The only possible conclusion was that the radio-active substance, on being treated with the acid, had formed a gaseous chemical combination. As there does not exist any gaseous compound of aluminium, while there is such a compound of the neighbouring element, phosphorus, which forms the gas phosphuretted hydrogen, the necessary assumption was that the radio-active substance formed from the aluminium was phosphorus.

The nuclear transformation might therefore have come about as expressed in the following equation:

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} = {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n}$$

For the radio-active phosphorus cannot be the phosphorus isotope $^{31}_{15}\mathrm{P}$ which we should get if the α-particle was simply absorbed by the aluminium nucleus, since the phosphorus isotope $^{31}_{15}\mathrm{P}$ is the isotope that constitutes ordinary phosphorus, which is not radio-active. Therefore during the process an uncharged particle must have escaped from the nucleus, and this, of course, means a neutron. The radio-active phosphorus isotope $^{30}_{15}\mathrm{P}$ which is thus formed is unstable, since it obviously contains an excess in charge in proportion to its weight, so that after a time it splits up in accordance with the equation:

$$^{30}_{15}\mathrm{P} = {}^{30}_{14}\mathrm{Si} + {}^{0}_{1}\mathrm{e}$$

for by emitting a positron $^{0}_{1}\mathrm{e}$ it is transformed into the stable silicon isotope $^{30}_{14}\mathrm{Si}$, which occurs in the naturally occurring silicon.

Like the natural radio-active substances, a radio-active substance of this kind, artificially produced, has a fully determined half-value period (which means the length of

time that elapses until the half of the substance has been transformed and the radiation has thereby fallen to half strength). For the above-mentioned radio-active phosphorus isotope a half-value period of 3 minutes 15 seconds was found.

This first example of an artificially produced radio-activity was soon followed by many others. At the time of the first Joliot-Curie investigations several similar processes were reported as having been obtained by the bombardment of various lighter elements by α-particles, and all these new radio-active isotopes sent out positrons, each with its determined half-value period.

These new radio-active substances produced by means of α-ray bombardment are therefore distinguished from those found in nature by their emission of positrons instead of electrons. But this does not mean that we must now assume that these substances contain positrons in the nucleus, any more than we have to assume that the nuclei of the ordinary β-radiating substances contain electrons. Just as the electron in a β-ray emission is not formed till the moment of the emission, so we must assume that in a positron emission a proton is changed into a neutron and a positron, as shown in the following equation:

$$ {}^{1}_{1}\mathrm{H} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{1}\mathrm{e} $$

The artificial radio-active substances can of course be produced only in infinitesimal quantities by this method, since the probability of the α-particles striking and transforming an atomic nucleus is so near vanishing-point that the quantities of the substances which are formed cannot be detected by weighing. On the other hand, there is no difficulty in detecting the presence of the substances while they are radiating, as our methods for doing this are so highly sensitive that we can detect the emission of even one particle only. Besides the cloud-chamber method there is also an electric

method, which is based upon what is known as the *tube meter*, which allows of the counting of single electrons.

The tube meter is a metal tube along whose length, inside the tube, is stretched an insulated metal wire. The tube is partly evacuated by pumping, and the metal wire is maintained at an electric potential of a few thousand volts. If now an electron or another charged particle comes into the tube meter, there is a short-lived electric discharge between the wire and the tube wall, and the weak jolt which this gives to the current can now be magnified by means of amplifying tubes or valves of the same kind as those used in radio receivers, so that it will make a click in a loud-speaker, or can be registered by means of a mechanical teller. Such tube meters are employed wherever work is being done on the artificial radio-active substances, and are a valuable supplement to the cloud-chamber.

The production of artificial radio-activity was the last term in the series of fundamental discoveries for which we have to thank the α-particles. Meanwhile new particles had been found which seemed to be possibly better fitted for bombardment than the α-particles, since the latter, because of their repulsion from the positive atomic nuclei, are not the most ideal projectiles. This has shown itself in the fact that they can make their way only into the lighter nuclei, which because of their lower charge exert the least repulsion. On the other hand, it was not difficult to suppose that the neutrons would be well adapted to this purpose, for they have not any charge, and consequently are not in the slightest degree repelled by the nuclei.

It was Fermi in Italy who first conceived the idea, and in 1934 he actually put it into practice. For this he took a neutron source made by mixing beryllium powder with an α-radiating preparation, and then caused the neutrons from this source to strike various substances. He then found that almost all the elements were made radio-active by such irradiation, and he was able by means of a tube meter to determine the half-value period for these substances. In

contrast to the radio-activity produced by α-ray bombardment, in this case ordinary negative electrons were emitted, so that in this respect conditions were more like those of natural radio-activity.

As an example of such a process we may take the irradiation of sulphur, which has only one stable isotope ${}^{32}_{16}S$, and which, when bombarded with neutrons, is transformed into a radio-active isotope of phosphorus, protons being emitted. The equation for the process is:

$$ {}^{32}_{16}S + {}^{1}_{0}n = {}^{32}_{15}P + {}^{1}_{1}H $$

The new phosphorus isotope is, however, other than the isotope ${}^{30}_{15}P$ found by Joliot-Curie through bombarding with α-particles, since, as we have said, it sends out electrons instead of positrons, and moreover it is transformed with the considerably longer half-value period of 15×24 hours. There is thus plenty of time to carry out chemical operations with the substance, and so to become thoroughly convinced that it has the chemical properties of phosphorus. It is quite true that the quantity of matter formed in the process is so small that it can be detected only by its radiation, but by adding a fair amount of ordinary phosphorus we can easily carry out chemical operations with the whole amount of phosphorus. Since radio-active phosphorus is only an unstable isotope of ordinary phosphorus, it will enter into exactly the same chemical combinations as the latter, and when the phosphorus is precipitated the radio-active substance must therefore precipitate with it, after which it is shown to be present by its radiation.

The phosphorus isotope ${}^{32}_{15}P$, as opposed to the isotope ${}^{30}_{15}P$, has too great a mass for its charge, and so one of the neutrons of the nucleus changes to a proton, emitting an electron. The transmutation equation becomes:

$$ {}^{32}_{15}P = {}^{32}_{16}S + {}^{0}_{-1}e $$

from which we see that in the end we get exactly the same substance as that which was originally irradiated with neutrons.

In a very short space of time Fermi and his fellow-workers did some wonderfully good work, which was carried out almost on modern industrial lines, "on the moving band", so to speak. The whole series of elements was subjected to a systematic bombardment by neutrons, during which even the heavier substances underwent elemental transmutations, with the formation of radio-active isotopes of substances whose atomic weights were approximately those of the final product. Several differing types of reactions were found: either, as in the example given, protons were emitted, or, in the case of other substances, α-particles or deuterons, while in many cases stable isotopes were formed. As one step in the investigations use was often made of chemical transformations on the same principles as in the example given with phosphorus, so that it could be shown with certainty which radio-active substance had been formed. On the other hand, no one has as yet succeeded in showing by chemical methods what is the final product which is formed from the radio-active substance; but this can be inferred from the nature of the radiation sent out. By applying the tube meter measurements were made of the rate at which the intensity of the radiation lessened, so that for all the radio-active isotopes it was possible to give the correct half-value period.

The use of the neutrons to produce artificial radio-activity was thus seen to be decidedly effective, and accordingly this method was at once adopted in all the laboratories in which anyone was lucky enough to have the needful quantities of α-radiating substances for producing the neutrons at his disposal. That the method spread so quickly was partly explained by the fact that the experiments themselves were almost as easy to perform as most of the ordinary school experiments in physics. To demonstrate artificial radio-

activity, for example, we take a bit of sheet silver and hold it for a minute or two close against a source of neutrons, when it becomes so strongly radio-active that by holding it up to a tube meter connected with a loud-speaker we get a real machine-gun fire of electron clicks in our ears. After a few minutes we shall clearly hear the clicks becoming farther apart, and if we time them it is a simple matter to determine the half-value period, which for silver is 23 seconds.

The one and only drawback to this method was that one had to have rather a powerful radium preparation at one's disposal, so as to get a sufficient abundance of neutrons to work with. The reason for this is, of course, that the very process by which the neutrons are produced is also a process of nuclear splitting, whose low frequency arises from the fact that only a small fraction of the preparation's α-rays happen to hit the nucleus. With a radium preparation of $\frac{1}{10}$ gramme, emitting about 10^{10} α-particles a second, the most we can attain is an output of about 10^5 neutrons a second.

The neutron sources used in practice consist either of the pure radium salt (radium sulphate), which is carefully blended with finely ground beryllium and put into a sealed glass tube, or else, if we happen to have a radium preparation dissolved in water, of a glass tube containing beryllium powder and gaseous radium emanation, which can be got from the radium solution. The latter method gives a somewhat greater yield than the former, but it has the drawback that after a few days the radium emanation has to be renewed, as the half-value period of the emanation is barely 4×24 hours.

That Fermi's investigations, despite the relatively few neutrons employed, resulted in so many transformations of elements, was due precisely to the inherent obtrusiveness of the neutrons, which do not withdraw before even the heaviest atomic nuclei. Fermi and his fellow-workers actually succeeded in devising a method which for certain processes

multiplied many times the power of the neutrons to split the nucleus, so that the yield of the irradiation could be increased up to 40 times. This method consisted in surrounding both the neutron source and the substance which it was proposed to irradiate with a thick layer of paraffin or water. As these substances contain a particularly large number of hydrogen atoms, the intensified action is explained by saying that the neutrons, through repeated collisions with the hydrogen nuclei, lose velocity, and that the *slow neutrons* thus produced bring about the nuclear transformations more easily. That it should be hydrogen-rich substances especially which have the power to slow down the neutrons arises from the fact that protons and neutrons have the same weight; for this means that the neutron at each collision will on the average lose half of its energy, so that after comparatively few collisions it has only an infinitesmal kinetic energy left.

It is, in fact, highly remarkable that the slow neutrons should be more efficient in nuclear transformations than swift neutrons, while from charged particles such as α-particles and protons we are accustomed to obtain a greater yield in proportion to their greater velocity. The nuclear processes in which the yield is increased by slowing down the neutrons are thus of a particular kind: for no real nuclear splitting takes place, but rather a building up, the neutron being caught up into the nucleus. In this way there is formed an isotope of the same element, in which the atomic weight is increased by 1 only, and the isotope can be either stable or radio-active. If the isotope formed is stable, the process of capture is accompanied by the emission of a quantum of γ-radiation, whose energy is equal to the cohesive energy between the neutron and the original nucleus.

The simplest example of such a process of capture is the formation of heavy hydrogen nuclei when neutrons are caught up into protons, which is found by experiment to happen when γ-rays are sent forth with energy of $2 \cdot 2$ million

volts. This process, which can be expressed by the equation:

$$_{1}^{1}\mathrm{H} + _{0}^{1}\mathrm{n} = _{1}^{2}\mathrm{H}$$

is therefore exactly the opposite of the nuclear photo-effect in heavy hydrogen discussed on page 148, and is carried out most easily when the neutrons are slow. So that when we have a neutron source surrounded by water or paraffin, the neutrons will first be slowed down by the collisions with the protons, and then will be captured by the latter. Provided the layer of water or paraffin is thick enough, capture will be the final lot of every one of the neutrons.

This is why the physicists use thick layers of water or paraffin to protect apparatus or persons against the aggressive neutrons. For in large quantities neutrons are at least as dangerous for the human organism as the rays from the radio-active substances.

It would take us too far here to enter into the great diversity of nuclear processes with which the Joliot-Curie and Fermi discoveries have enriched physics. We must be satisfied with the foregoing reactions as typical examples of some of the most important kinds of processes. On the other hand, we cannot leave this fascinating department of physics without mentioning the fact that important practical applications of artificial radio-activity have already been made. In particular, attempts have been made to apply these substances to biological or physiological problems by a method which we owe to G. von Hevesy of Hungary, and which is known as the *Indicator method.* The principle here consists in using the radio-active isotopes as indicators of the corresponding stable isotopes, as they can be so readily detected by their radiation, even if there are only a very few atoms of them. Thus we are able, so to speak, to put marks on the individual atoms, so that we can always recognize them among countless others, just as we fit a carrier-pigeon with a ring round the leg, so that we shall know it again and so that we can follow its flight.

It is more especially the phosphorus isotope $^{32}_{15}P$, produced by irradiation with neutrons, which has been used as an indicator, because of its relatively long half-value period. We can study the changes undergone by phosphorus in human or animal organisms, by giving the animal employed for the experiment a phosphorus preparation to which has been added a trifling amount of radio-active phosphorus. As the radio-active phosphorus will accompany the natural phosphorus through all the chemical transformations in the organism, and always in the same quantitative ratio, all that is needed is to employ a tube meter to trace the radio-activity in the various organs or in the excreted waste products in order to learn how quickly and in what amounts the phosphorus is distributed throughout the organism. By such methods a considerable mass of data has already been obtained concerning the distribution and assimilation of phosphorus and other substances in various tissues, bones, etc.

The indicator method had already been worked out long before the discovery of the artificial radio-active substances, and had been applied by using natural radio-active ones, in which, however, its application was limited to such substances as bismuth and lead, for which there are natural radio-active isotopes. Since the discovery of artificial radio-activity the method, however, has found a far wider field of application, as we are now in a position to produce radio-active isotopes for most of the vital elements. Finally, it should be noted that this method will, in all probability, prove important in respect of problems of a chemico-technical kind, since radio-active isotopes of most of the metals can be obtained.

THE TECHNIQUE OF EXPLODING THE ATOM

The immense field of research that has been opened up through the discovery of artificial radio-activity, and the

fact that great things may be hoped from its practical application, has inspired efforts to prepare these substances by *wholly* artificial methods; that is to say, without making use of α-rays or neutrons produced by α-rays. These efforts are directed more especially towards raising the yield of the nuclear transformations, which in both the methods hitherto employed is limited by the strength of the radio-active preparations at our disposal. The principle of these new methods is just the same as in Cockcroft and Walton's first wholly artificial splitting of the atom; namely, to accelerate small charged particles with as high electric potentials as possible. The most direct process is to set up a high-tension plant which can yield a potential of 1 million volts, or perhaps rather more, and then direct this potential into the discharge tube in which the charged particles are to be accelerated. In recent years the technique of these experiments has undergone such great development that it is now comparatively easy to set up a high-tension plant with the requisite potential and with a current of some milliampères.

There are two essentially different methods used for producing high direct potentials. One consists in making use of an alternating current, which by means of transformers is transformed to as high a potential as is needed, after which it is rectified by means of what are known as valve tubes, which, like the valves or tubes in a radio receiver, allow the electricity to pass only in one direction. Lastly, such a plant usually includes some condensers, whose object is to damp the oscillations in the potential which may still be present after rectification. Plants such as this have shown they will work reliably up to 1 million volts, and a current of 10 milliampères. Fig. 33, Plate VI, page 149, shows a high-tension plant with this capacity. At the very top of the plant, which is 8 metres in height, we see two great copper balls 1 metre in diameter, which serve to measure the potential;

for if the balls, whose distance apart can be varied, are placed so far apart that sparks can just leap the gap between them, this distance is a measure of the tension.

A widely different and extraordinarily interesting method for producing high tension has been worked out by van de Graaf in America. It is based on the same principles as the old-fashioned electrical machines which will be found in any school equipment of physical apparatus. The high tension is built up as electrical charges are incessantly carried along on a conductor, which is insulated, so that the charges cannot escape. While in the school apparatus the charges are carried on a revolving glass or ebony disk, van de Graaf uses long, broad straps or belts of silk, running round two pulleys. One of these pulleys is fixed on the ground, where the belt is charged with electricity, while the other is housed in the conductor which we have mentioned, which has the form of an insulated hollow metal sphere, and is fixed at a height of several metres above the ground. As the metal sphere receives higher and higher potentials, greater and greater energy must be applied to draw up the belt with its charges against the powerful repelling forces radiating from the metal sphere.

With the largest example of this kind of apparatus, which was completed in America in 1936, the fantastic potential of 5 million volts has been attained with a current of 3–4 milliampères. Fig. 34, Plate VI, page 149, shows a rather smaller apparatus of the van de Graaf type, which for several years has been used for nuclear splitting by the Norwegians Tuve, Hafstad and Dahl in America. The metal sphere and the belts are seen at the top of the picture, while the long vertical tube in the middle is the discharge-tube in which the ions are accelerated. The tube passes through the floor to the storey below, where the irradiation is carried out. For both types of high-tension apparatus alike all dimensions and all distances from the walls must be very great, for sparks

several yards in length are not unusual with such high potentials.

The technical problem of making high-tension apparatus with high enough potentials and with a strong enough current for experiments in splitting atoms may now be said to have been solved. The difficulty of such experiments resides in making discharge tubes work reliably with these potentials. These discharge tubes, which are of glass or porcelain, must have very large dimensions to prevent sparks from leaping along the outside of the tube. On the top of the acceleration tube proper, which must always be pumped as free of air as possible, is placed the source which is to supply the needful hydrogen or helium ions, which in the acceleration tube attains the great values of energy corresponding to the high tension. At the lower end of the tube the substances are placed which are to be bombarded with the particles, as also the requisite pumps and registering appliances such as cloud-chamber, tube meters, and so on. The highest potentials with which such a tube has been operated up to date are in the neighbourhood of 1 million volts, but some difficulty is encountered as regards the strength of the current, for not much more than about $\frac{1}{10}$ milliampère has been reached.

Even though a modern gun such as this for bombarding the atom, consisting of a high-tension apparatus with a discharge tube metres in length, has a most imposing effect, and may give splendid results, it is outdone in its results by an apparatus recently designed by Lawrence of America. The idea on which its construction is based is as follows: the particles are not immediately subjected to the high potential, but are accelerated step by step, by making them go through the same comparatively low potential many times in succession.

The apparatus, known as a *cyclotron*, consists first and foremost of a gigantic electro-magnet, whose task it is to deflect

the charged particles, so that they come to describe circular paths, whose diameter becomes greater as their speed increases. The particles obtain their velocity from the attraction and repulsion of two electrodes which are placed between the poles of the magnet; a schematic drawing of these is shown in Fig. 35, where the two poles of the magnet must be conceived as lying above and below the plane of the paper. The electrodes, which are hollow, have the shape of an empty

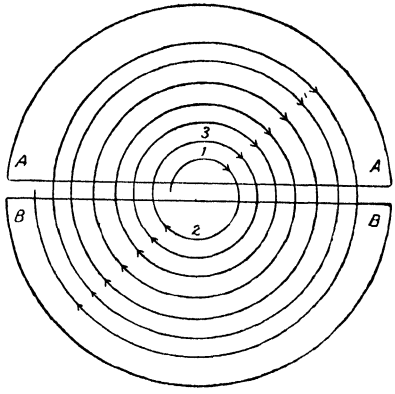


Fig. 35

blacking tin sawn in two, but their dimensions are a great deal larger, the diameter being as a rule about 1 metre. About half-way between the electrodes is a device for obtaining the needful ions, which at the outset have quite a low velocity, so that they are deflected by the magnet into a path with a very small radius. When one of these positive ions has travelled through the hollow space in electrode A, as shown by path 1 in the figure, it is so arranged that A is positively and B negatively charged, so that the ion in the space between A and B may be given an increased velocity, corresponding to the difference in potential between A and B. Because of this increase of velocity the ion will describe a slightly wider semicircle 2 within the electrode B. While it

is inside B, the potential on the electrodes is reversed, so that B is positively and A negatively charged when the ion reaches the space between them. The ion will thus again be given an increased velocity as it passes between the electrodes, so that the semicircle 3 in electrode A becomes still greater. The potential being again reversed while path 3 is being covered, the particle is given a further increased velocity the next time it traverses the space between A and B; and so the process goes on.

In this way the ions are continually revolving with a constantly increasing velocity, in a spiral path which is made up of ever-widening circular paths, until they have swung out as far as the edge of the electrodes, where they are drawn out of the magnetic field by a special electrode, which is not shown in the figure. To bring about the needful changes of potential in the electrodes an alternating generator is employed, in which the direction of the current changes about 20 million times a second. A high-frequency alternating current like this cannot be produced by an ordinary generator, so that a short-wave transmitter must be used. As the said oscillation-number of 20 million hertz (20,000 kilohertz), corresponds to electro-magnetic waves with a wave-length of 15 metres, this transmitter must be of the same type as those that are used in short-wave broadcasting.

The condition for the successful operation of the cyclotron, when an alternating current with a constant oscillation-number is used, is that the ion should take exactly the same time for passing over each of the paths 1, 2, 3, etc. And happily Nature is kind enough to see that this condition is fulfilled. It is true that path 1 is shorter than path 2, but to make up for this the ion moves more slowly in path 1 than in path 2, and a careful calculation shows that these two factors exactly balance each other, so that the time taken for a given ion to make the circuit is independent of its speed and depends only on the strength of the magnet. We therefore have

PLATE VII

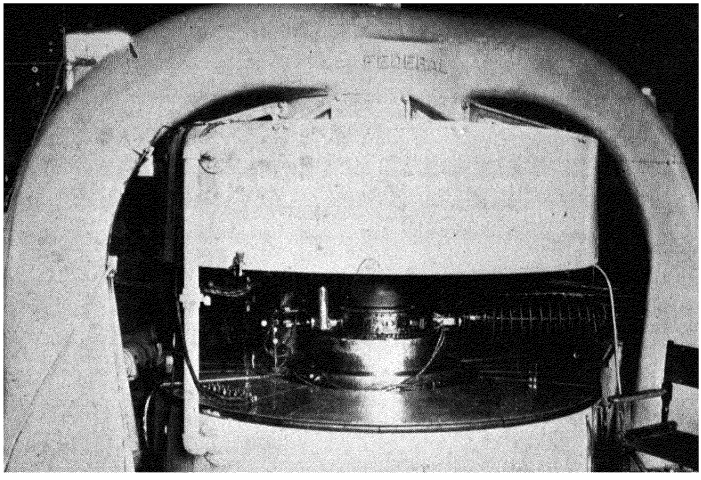


FIG. 36.—Lawrence's Cyclotron. The dimensions can be seen by comparing it with the chair on the right.

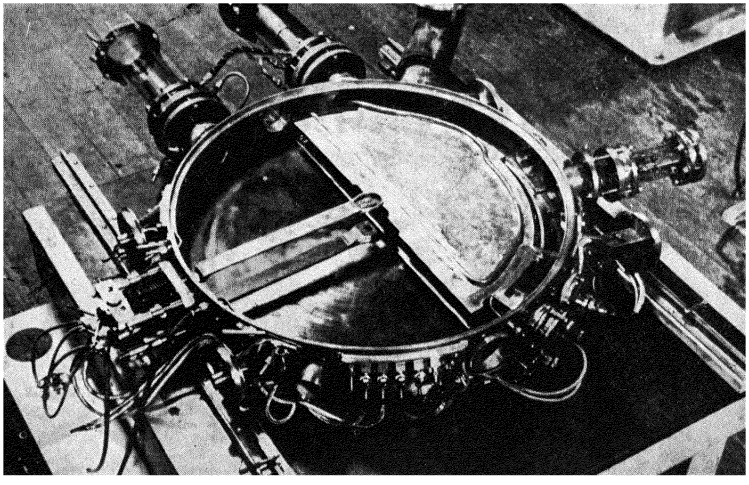


FIG. 37.—Inside the Cyclotron. The diameter is 70 cm.

PLATE VIII

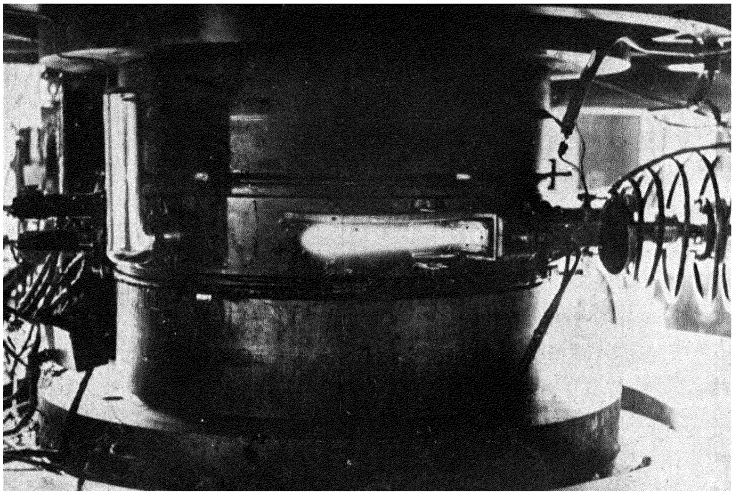


FIG. 38.—The Cyclotron at work. The luminous ray in the centre consists of deuterons with a velocity corresponding to 6 million volts.

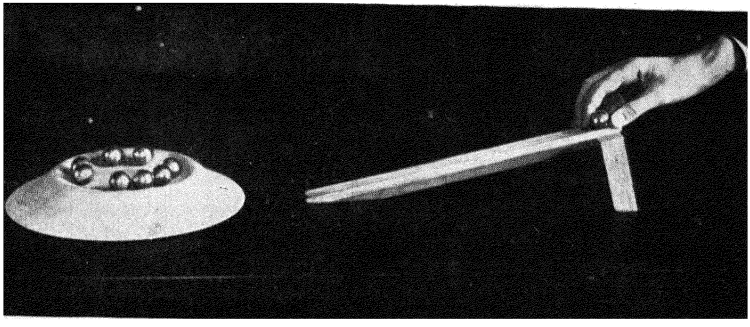


FIG. 39. Illustration of the bombardment of an atomic nucleus by high-speed particles.

only to adapt the strength of the magnet to the alternations of the short-wave transmitter in such way that the half-circuit of the ions in one of the semicircles is covered in the right time, and then this will automatically hold good for all the paths. If now we use a potential on the electrodes of, say, 50,000 volts, and pass the ion 100 times through the space between the electrodes, it will emerge with a velocity which is as great as if it had passed once through a potential of 5 million volts; and it should be noted that this is effected without higher potentials than the 50,000 volts actually employed, so that all the drawbacks of applying potentials of a million volts are avoided.

However fantastic all this may sound, Lawrence and his fellow-workers did succeed in making such a cyclotron work, although it called for many years' labour and much technical ability. First the mighty magnet had to be made, which, besides having the necessary strength, had also to be so contrived that there was room between the poles for the electrodes and all the needful auxiliary apparatus. Lawrence was able to get hold of a big electro-magnet from what is known as a Poulsen generator, which was formerly much used in wireless telegraphy, but which in our day has been replaced by the modern valve transmitters. The accelerating system, consisting of the electrodes, the source of the ions, etc., was now put into a metal box from which the air could be exhausted, and which could be easily put in or taken out from between the poles of the magnet, so that the changes required by the experiments could quickly be made. Fig. 36, Plate VII, page 164, shows Lawrence's cyclotron, and where we see the metal box placed between the two gigantic coils of the magnet and its pole-pieces, which had a diameter of 70 cm.

In Fig. 37, Plate VII, page 164, is shown the metal box withdrawn from the magnet, so that we can see the parts contained within the electrode, the pump tubes, etc. One of the two hollow electrodes has been removed, so that the

other can be more plainly seen. Lastly, Fig. 38, Plate VIII, page 165, is a close-up photograph of the cyclotron at work; the high-speed ionic ray is emerging through a small window. The energy of the ray is so great that its range is about ½ metre in the air, and this is clearly shown by the fact that the air along the path of the ray is so strongly ionized that it emits a powerful light.

Lawrence's method is undoubtedly, for the moment, the most effective means of splitting the atom, for by the use of protons, deuterons, and helium ions nuclear actions on a hitherto undreamt-of scale have been produced. It is true that the currents which have been employed up to now are only about $\frac{1}{10}$ of those that can be attained in a discharge tube by employing the direct method with very high potentials; nevertheless, the results are very impressive. In particular deuterons have been used, which have shown themselves well fitted to be employed as artillery in many processes, and in these they have reached velocities corresponding to over 8 million volts, to the number of 4×10^{13} deuterons per second. The latest news we hear from America (1937) is to the effect that the experimenters have now succeeded in working with *doubly* charged helium ions—that is, with pure helium nuclei—and thus in producing artificial α-particles with velocities corresponding to 12 million volts, and in amounts that are several thousand times greater than those which can be obtained from ordinary radio-active preparations. When we bear in mind that a cyclotron will probably cost not so very much more than one gramme of radium (say £10,000), and that it can yield some thousands of times as many α-particles, which are also several times richer in energy, we can understand that the cyclotron is an invention with a future before it. It is not astonishing that cyclotrons are now being set up in many physical laboratories, both in America and in Europe.

The apparatus here described has not only transformed

the physical laboratories into great airy machine-halls, but it has also given us the means of effecting so many new and various kinds of atomic transformations that there will soon be a considerable literature on the subject. Here, however, we will confine ourselves to mentioning only a few of the most interesting processes—as, for instance, bombarding heavy hydrogen with deuterons, which is done with a high-tension apparatus. By bombarding a small piece of "heavy ice"—that is, ice produced by freezing heavy water—with high-speed deuterons, two wholly different transformations are found, one of which can be expressed by the equation:

$$_1^2\mathrm{H} + {}_1^2\mathrm{H} = {}_1^3\mathrm{H} + {}_1^1\mathrm{H}$$

Thus there is formed an ordinary proton together with a hydrogen nucleus with mass 3 hitherto unknown, but whose existence was here established through cloud-chamber photographs. This hydrogen isotope, whose nucleus must therefore consist of 1 proton and 2 neutrons, is to all appearances stable, but it has not been detected with certainty in nature. The process described is characterized by the fact that all the particles entering into it are atomic nuclei of one and the same element, though they take the form of three different isotopes.

Besides this, it was found in performing the same experiment that the process often follows quite a different course, which is expressed in the equation:

$$_1^2\mathrm{H} + {}_1^2\mathrm{H} = {}_2^3\mathrm{He} + {}_0^1\mathrm{n}$$

where there is formed a hitherto unknown stable isotope, namely the helium isotope $_2^3\mathrm{He}$, whose nucleus must be made up of 2 protons and 1 neutron. Further, a great many neutrons are emitted, so that the process finds direct application as a neutron source.

Another important nuclear process, for which the cyclotron is well adapted, occurs when beryllium is bombarded

with deuterons. Here again we get a very heavy neutron emission, in accordance with the equation:

$$^{9}_{4}\mathrm{Be} + ^{2}_{1}\mathrm{H} = ^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n}$$

while at the same time there is formed the stable boron isotope $^{10}_{5}$B. This process has been given a wide application as a substitute for an ordinary neutron source, as it is the best method known for producing neutrons. By using deuterons with a velocity corresponding to 5–6 million volts and a current of only $\frac{1}{100}$ milliampère a yield has been reached of no less than 10^{10} neutrons a second, which is equal to what we should obtain from an ordinary neutron source by using 10 kilogrammes of radium. This is perhaps one of the most convincing examples of the progress effected by the cyclotron, since the entire sum of the radium hitherto extracted is less than one kilogramme.

Where such quantities of neutrons are employed the problem of protecting human beings against the harmful effects of the neutrons becomes extremely important. Since the human body, for the most part, is made up of water, the neutrons, on colliding with the protons contained in water molecules of the organism, will yield up considerable quantities of energy to these protons, which may then cause great damage owing to their ionizing action. When work is being carried on with artificial neutron sources produced either by high-tension apparatus or by the cyclotron, thick barricades are therefore set up, consisting of tin cans filled with water, and care is also taken that the experimenters are as far from the source as possible.

The mighty instruments with which atomic physics has been endowed in the shape of the gigantic apparatus here described, are, of course, still very far from having been put to their fullest use. But all the nuclear transformations which had been discovered by the use of α-particles or neutrons have already been repeated, and besides this many new processes

have been devised, and a great number of new artificial radio-active elements have been produced. The number of artificially produced radio-active isotopes is according to the latest statements something over 200; that is to say, about as great as the number of the known stable isotopes, to which must be added the 50 or so well-known natural radio-active isotopes. Taking everything together, then, we now have knowledge of about 500 isotopes of our 90 or so different elements, which gives on an average more than 5 isotopes for each element.

Although the alchemist's old dream of changing one element into another is thus being fulfilled every day in the world's physical laboratories, the trivial question is often asked, whether we can now make gold. This substance, indeed, has in no way a special position among the other elements, so it is natural that processes should have been discovered by which both radio-active and stable gold isotopes are formed. As we may presume that the reader is most interested in a stable form of gold, we will disclose the way in which it is made. A piece of platinum is taken, and it is irradiated for some hours with high-speed deuterons from a cyclotron. The following is the reaction that takes place:

$$^{196}_{78}\mathrm{Pt} + {}^{2}_{1}\mathrm{H} = {}^{197}_{78}\mathrm{Pt} + {}^{1}_{1}\mathrm{H}$$

The new platinum isotope $^{197}_{78}\mathrm{Pt}$ formed is, however, radio-active, and is transmuted with a half-value period of 15×24 hours, electrons being emitted, as shown in the following equation:

$$^{197}_{78}\mathrm{Pt} = {}^{197}_{79}\mathrm{Au} + {}^{0}_{-1}\mathrm{e}$$

where the end product $^{197}_{79}\mathrm{Au}$ is quite ordinary gold. The method cannot, however, be called a paying one, as the output, in spite of the gigantic apparatus used, and the many kilowatts needed to keep the cyclotron going, is always so small that with our present resources we should have to

continue the irradiation for 10^{10} years to get 1 gramme of gold formed. Even if with future improvements the output should come to be materially raised, any physicist or chemist would rather keep his good sheet of platinum, which in contrast with gold is an extraordinarily useful metal, and is largely employed in the chemical industries.

There is another and more reasonable question which is often asked of the physicist: namely, whether artificial radium can now be produced. To this the answer will still most assuredly be in the negative, and yet highly encouraging, since substitutes can be made which in certain cases are fully as good or even better than the natural radium. For what makes radium so valuable is merely its radiation, and now artificial radio-active substances have been produced in such amounts and with such high radiation qualities that they already are fit to compete with radium in respect of scientific medical applications. The most important of these substances is the radio-active sodium isotope $^{24}_{11}Na$, which can be produced in several different ways, and which in its transformation with a half-value period of barely 15 hours sends out both β-rays and γ-rays with an energy of some millions of volts. By means of the cyclotron this radio-active sodium has been produced in such great quantities that we can obtain the same γ-ray strength as from a radium preparation of 1 gramme, which in medical science is regarded as a very strong preparation.

The future will show whether the wonderful tale of radium, after its forty years' romance, is to have its Finis written by the fantastic discoveries of these last few years—discoveries which seem to beckon us on toward new and still more glorious adventures.

THE NUCLEAR THEORY AND ATOMIC ENERGY

All the great epoch-making discoveries described in this last section have been of a purely experimental kind, but

already, in the course of a few years, they have brought together such a great body of material that the time will presently seem ripe for attaining by theoretical cogitation a deeper understanding of the structure of the atomic nuclei.

The conclusion to which the latest research has led us so far as to the constitution of the nuclei, is that all nuclei are built up of protons and neutrons. This must be regarded as sufficiently proved, partly by the fact that by our experiments in nuclear splitting we have obtained protons and neutrons from the nuclei, and partly because all atomic weights are seen to be very nearly an integral multiple of the weight of the proton or the neutron. Refined mass spectroscopic methods have shown with certainty that the atomic weights of the isotopes betray small deviations from the whole numbers, these deviations being such that the weight of a given atomic nucleus is always found to be slightly less than the total weight of the protons and neutrons making up the nucleus.

However, these deviations do not by any means signify that there is anything wrong about our assumption as to the structure of the nuclei; on the contrary, they lend support to this assumption. For the deviations arise from the fact that the nuclei, when they were being built up long ages ago, must have emitted a considerable sum of energy, corresponding to the cohesive energy of the particles; and since Einstein has taught us that energy and mass are one and the same, a loss of energy such as this means also a loss of mass. We now quite simply obtain the cohesive energy by multiplying this loss of mass by the square of the velocity of light.

If in the phenomena of every-day life we do not perceive that energy and mass are bound up together in this way, this is explained by the fact that even the greatest amounts of energy which we can put into a body or take out of it result in such infinitesimal changes in the body's mass that we cannot detect them by weighing. A litre of water, for instance,

which is heated from 0 to 100 degrees will acquire an addition to its energy which results in the water becoming only about 10^{-8} grammes heavier; and this increment lies far below the degree of precision with which 1 litre of water can be weighed. But things are quite otherwise with the atomic nuclei, where the cohesive energy between their components is so great that the mass corresponding to it is not infinitesimally small compared with the mass of the nuclei. Therefore it was that Einstein's momentous prediction was first confirmed by the nuclear reactions, as has already been mentioned in connection with Cockcroft and Walton's experiment (page 136).

By measuring the difference between the mass of an atomic nucleus and the total mass of its components and multiplying this difference by the square of the velocity of light, we obtain the cohesive energy for the nucleus in question. Now it is not customary to give the absolute weight in grammes of the atomic nuclei, but to give it in the ordinary units of the atomic weight, the atomic weight of oxygen being fixed as 16, and the calculations show that *a mass of* 1 *atomic weight unit corresponds to an energy of* 931 *million electron-volts.*

We shall try to calculate the energy for one or two important atomic nuclei, using the latest measurements for the atomic weights. The exact atomic weight of hydrogen is 1·00813, while that of the neutron is 1·00897. If these numbers are added together we get 2·01710, while the atomic weight of heavy hydrogen is 2·01473. The loss in mass when a deuteron is formed from a proton and a neutron is therefore 0·00237, which, multiplied by the 931 million mentioned above, gives us the cohesive energy of 2·2 million volts (cp. page 157). If we repeat exactly the same reckoning for a helium nucleus, we find the sum of the weights of the two hydrogen atoms and the two neutrons to be 4·03420, while helium's atomic weight is only 4·00389. The loss in

mass when an α-particle is formed is therefore 0·03031, which gives the cohesive energy of 28·2 million volts.

The great cohesive energy of α-particles means that the protons and the neutrons in them are bound especially strongly together, which is revealed in the fact that the α-particles are extraordinarily stable nuclei. We find, too, that the processes of nuclear splitting whereby α-particles are formed are distinguished by an exceptionally great development of energy, which manifests itself in the high velocities of the emitted α-particles; as, for instance, in the splitting up of lithium by protons.

In this way, from the determinations of the atomic weight, we can work out the cohesive energy for all atomic nuclei; that is to say, the energy which would have to be supplied in order that the nucleus should be split up into its component parts. For the heavier atomic nuclei energies of 1–2 thousand million volts are required. Further, as regards the cohesive energies, the transformation of energy in any process of atomic splitting can readily be calculated, merely by comparing the masses of the atoms concerned before and after the process. In many cases it has been possible, as in Cockcroft and Walton's experiment, to check the calculated amounts of energy by measuring, for instance, in the cloud-chamber the range of the emitted particles; and in all cases the closest agreement has been found.

Even though the foregoing considerations have led to extensive knowledge concerning the energy of the atomic nuclei, and the transformation of energy in most of the known nuclear reactions, yet the physicists cannot rest content with this. There are many other problems relating to the atomic nuclei of which we should like to obtain a deeper understanding; such questions, for instance, as why nuclear reactions follow the course they do, or why certain nuclei are stable, while others are radio-active. Bohr, in his day, was able to account, in his atomic theory, for the properties

of all the elements, by starting from the grouping of the electrons in the atoms. Something like this is what we now wish to do for the properties of all the isotopes.

But when the problem of the nucleus is attacked, the situation is quite other than that which we encountered in 1913 in the problem of the atom, when through Rutherford's detection of the atomic nucleus we had reached certain definite conceptions as to the constitution of the atoms. For then we knew the electric forces with which the constituents of the atom acted on one another, so that at that time the problem was to discover the new laws of quanta mechanics governing the atoms. For the atomic nuclei the case is exactly the opposite, since we have to assume that the theoretical laws of quanta now known to us must also hold good for the motions of the constituent parts of the nuclei, whereas we know nothing whatever to start with about the nature of the forces which must be assumed as reciprocally operative between these constituent parts.

We can, however, get a rough idea of the dimensions and the mode of action of the nuclear forces by bringing to bear our knowledge of the cohesive energy and of the extent of the atomic nuclei. We already obtained some idea of the size of the atomic nuclei from Rutherford's experiments in 1911 on the diffusion of the α-particles, since from these experiments we could fix the diameter of the nuclei at approximately 10^{-12} cm. The heavy bombardment of the nuclei in more recent years has further confirmed this value, as from the frequency with which different kinds of ordnance hit and transform a nucleus we can work out a pretty certain value for the dimensions of the nucleus. In the result, the diameters of all the atomic nuclei lie within the limits $\frac{1}{3} \times 10^{-12}$ cm., which is the diameter of the hydrogen nucleus, and about 2×10^{-12} cm. for the heaviest nuclei; so that the latter are only about 6 times as great as one of the elements building up the nucleus, the proton, which indeed has practi-

cally the same dimensions as the neutron. Consequently the volume of the heaviest nuclei will be about $6^3 = 216$ times as great as the volume of a proton or a neutron. As the heavy nuclei contain rather more than 200 particles altogether, the atomic weight for uranium, say, being 238, it is to be concluded that all the particles in the nucleus lie as tight-packed as herrings in a barrel.

We begin to realize how heavily concentrated the mass must be in the atomic nuclei when we learn that a handful of nuclei, if as tightly packed as the protons and neutrons in the nuclei, would weigh 10^8 tons, which means as much as 10,000 ocean-going steamers of 10,000 tons each. This, of course, is only an imaginary experiment, since under such ordinary conditions we cannot get the nuclei to lie so closely together.

At first sight we cannot but be amazed that it should be possible for the many particles in an atomic nucleus to hold together in so small a space, particularly as about half of them are positively charged, and so, in accordance with the ordinary laws of physics, ought to repel one another. But since it is the fact that they do hold together particularly well, the nuclei being markedly stable, there must be enormous attractive forces at work, and forces of a kind up to now unknown; forces that fully overcome the electrical repulsions. Evidently these forces can act only over very small distances, of the same order of dimensions as those of the nuclei, for a proton which has just escaped from the cramped nucleus, is acted upon only by the ordinary electric repulsion. We obtain some idea of the measure of the cohesive forces if we remember that as a rule an energy of several million electron-volts must be applied merely to tear one of the components of the nucleus away from the field of action of the nuclear forces.

The tight packing of particles in the atomic nuclei means, therefore, that we are confronted with a situation that is

wholly different from that presented by the electron system of the atoms, where the distances between the single electrons are so great, compared with their size, that there is far more empty space than matter. In contrast with such an electronic system, which to a great extent recalls the conditions in a gas, an atomic nucleus can best be compared with a solid ball or a drop of fluid, which are characterized by a strong reciprocal action between the single particles. This point of view has of late been strongly stressed by Bohr, who in his fundamental works of 1936 and 1937 has shown that we can go far towards accounting for the atomic nuclear reactions on quite simple considerations.

To illustrate what happens when a high-speed particle strikes an atomic nucleus, we will resort to a mechanical model which has been utilized by Bohr. This model, of which a picture is seen in Fig. 39, Plate VIII, page 165, consists of a set of steel balls placed in a bowl-shaped hollow in a wooden block. The balls are to represent the protons and neutrons in the nucleus, while the rim around the hollow shows the outline of the nucleus. The purpose of the hollow is to hold the balls together, which in the actual atomic nucleus is done by the reciprocal forces of attraction between the particles. The sloping run is to give the balls the speed required for making their way into the "nucleus," and thus it corresponds to a high-tension apparatus. If in the beginning there are no balls at all in the bowl, and a ball is rolled down into it, this will run up over the rim surrounding the hollow and then fly out of the bowl on the opposite side with the same speed as that with which it entered. If, on the other hand, there are already other balls in the bowl, the closer they lie together the greater the probability that the new arrival will strike one of them. If they lie so close that they touch one another, and more or less fill up the whole hollow, a new arrival will certainly strike one of them, which will thus be set in motion. This ball will then transfer some of its

kinetic energy to its neighbours, so that the energy of the incoming ball will very quickly be distributed over all the balls, which thus will be set in brisk motion. If there were no friction or other resistance to the motion of the balls, they would continue their reciprocal collisions until it happened that one of the outermost balls was given so much energy that it could run up the slope and escape from the bowl.

In the real atomic nucleus the conditions are exactly the same. If a neutron or a proton is shot into the nucleus, it will at once share its energy with the other nuclear particles, so that after a very brief lapse of time it cannot be said any longer to be in any special position among them. Thus a new nucleus has been formed, made up of the original nucleus with one added neutron, but with an excess of energy. This nucleus will now, as a rule, have only a limited lifetime, since there may arise a chance concentration of the energy upon one of the particles, which then, if the energy is great enough, will be flung out of the nucleus. The particle expelled may be either a proton or a neutron, or it may be a system of several particles, as, for instance, an α-particle; but there is no reason to assume that the particle which originally went in has a greater chance than the others of being flung out.

The assumption of such a more or less long-lived intermediate product in every nuclear process has shown itself to be in many ways of essential importance for the understanding of these processes. This is especially true for the pure processes of capture, where a slow neutron is captured which has not enough energy to make it highly probable that a particle will afterwards be expelled. The surplus energy is then sent out in the form of γ-radiation, which in the mechanical model would correspond to a state in which the balls gradually lost kinetic energy through friction, so that they come to rest without any of them leaving the bowl. In other nuclear processes, where there is a bombardment with a high-

speed neutron, it often happens that the particle sent out is another neutron, but with less energy than the incoming one. This can easily be understood from the model, since the probability that the *whole* energy should be again concentrated on a single particle must naturally be extraordinarily small.

In the theoretical treatment of the nuclei we can sometimes make use of the methods and conceptions known to us from the theory of heat, which tell us that the heat-content and

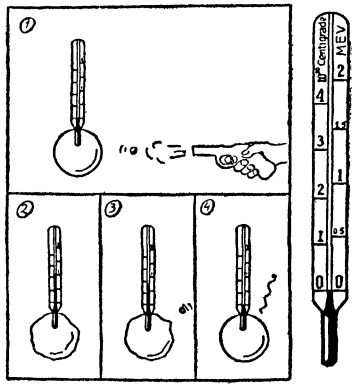


Fig. 40

the temperature of a body are nothing more than expressions of the motions of the atoms or the molecules. In an atomic nucleus the movements of the constituent parts can likewise be roughly conceived as a kind of heat motion, so that instead of giving the energy-content of the atomic nucleus in millions of volts we can just as well express it as a temperature measured in degrees centigrade.

In the "film drama" reproduced in Fig. 40 we see what happens to the energy when a high-speed particle is shot into a heavy atomic nucleus, in which has been placed an imaginary thermometer for measuring the energy. This "thermometer," which is seen at the side on an enlarged scale, has two graduated scales, on which the energy can be read off either

in millions of volts or in degrees centigrade, each division corresponding to 10^{10} degrees. When the ball has forced its way into the nucleus, the temperature is seen to have become alarmingly high, which means that the constituent parts of the nucleus have been set in violent motion, which is shown also by the uneven outline of the nucleus. The subsequent sending forth of a particle is, then, a process analogous to the evaporation from a fluid, where only the swiftest molecules have energy enough to escape. Just as the temperature of a fluid falls during evaporation, so the emission of a high-speed particle from the nucleus brings with it a very heavy fall in temperature, and this also is shown in the figure. But the comparison has the very great defect that many molecules must evaporate from a fluid before the temperature falls so heavily that the evaporation comes to an end, while the temperature of the nucleus, even after only one particle has been emitted, falls so heavily that it is utterly unlikely thereafter that the remaining energy will again concentrate itself on some one particle. As a rule, therefore, the last act will consist in the rest of the energy being emitted as electromagnetic waves, after which the nucleus becomes "free from fever" and goes back to its normal "round" form again.

The considerations which we have just set forth contain, under their light-hearted exterior, certain points of view which go to the very roots of the problems of the structure of atomic nuclei and the reciprocal action between their parts. By advancing these points of view Bohr has opened the way for a theoretical treatment of the problem of the atomic nucleus, and has thereby led the way to a comprehensive survey of the great stock of data which experimental nuclear physics has given us. We may hope that with a continuance of the co-operation between experimental and theoretical research we shall in the very near future reach an understanding of the nature of the nuclear forces, and of the problem of the stability of the isotopes.

Before we pass on from this last phase in the vast development of atomic physics, there is one question which must be answered, and that is the question as to the possibility of drawing upon the energy in the atoms, and putting to practical use the immense forces at work between the structural elements of the atomic nuclei. We often hear it asserted, for example, that in a brick there is so much atomic energy that it would drive an ocean-going steamer many times across the Atlantic, and that the only question is how to draw upon this energy.

We must, therefore, begin by examining what truth there is in this assertion, and we must also be clear as to what is meant by atomic energy. If we first of all consider the energy which, according to Einstein, would be brought into being if the whole mass of a body could be changed into energy, it is a simple matter to calculate the energy which would be contained in a brick weighing 1 kilogramme. We shall obtain a fantastic number—10^{10} horsepower-hours—which is more than enough for the proposed voyage across the Atlantic, since it would enable the steamer to sail the ocean for several years without a stop. We should be well supplied with energy for a period of time beyond all reckoning, if such a complete transformation of mass into energy could be brought about, which does not, however, look very likely. It is true that we have learned of late years that such transformation processes can occur under certain circumstances. We have in mind here the phenomenon that was discussed in the section dealing with the discovery of the positron: namely, that an electron and a positron can vanish and a quantum of radiative energy be created, corresponding to their mass. It is to be feared, however, that it will never be possible to exploit this phenomenon as a source of energy, for the simple reason that the process in question cannot be brought under man's control, for the positrons cannot be gathered together and stored, for immediately after birth they automatically unite

with electrons, which are to be found in plenty everywhere and in every substance. If, then, by atomic energy we understand that energy which would come into being if the *whole* atom disappeared, then physics gives us not the slightest grounds for hoping that we may one day be able to tap it.

If, on the other hand, by atomic energy we understand the energy which we should obtain if we could make use of the mighty forces by which the parts of the atomic nuclei hold together, then the problem becomes somewhat different. But we must first remember that energy cannot of course be won by *splitting* an atomic nucleus up into its separate parts, for such splitting always calls for the application of energy to overcome the forces of attraction between the particles. On the contrary, we should have to *build up* atomic nuclei from protons and neutrons, for by such a building up energy would be set free: namely, the cohesive energy which is yielded by the cohesive forces when particles unite and form nuclei. This energy, which corresponds to the loss of mass by the nuclei when they are built up from their parts, is about 100 times less than the energy corresponding to the mass of the whole atom, but it is still large enough to arouse hopes in simple souls of changing our life on earth at one stroke into a life of lotus-eating.

Such a process of building up atomic nuclei would be fully analogous to the chemical processes that are utilized when coal or hydrogen is burnt. When coal is burnt, what happens is that carbon atoms combine with oxygen atoms from the air, each atom of carbon combining with two atoms of oxygen to make a molecule of the chemical compound carbon dioxide. The reason why this process takes place with the development of considerable energy is that between carbon atoms and oxygen atoms, when they are brought closely enough together, strong forces of attraction of an electrical nature are at work. The opposite process, whereby carbon dioxide is split up into carbon and oxygen, on the other hand,

needs a considerable application of energy to overcome the forces of attraction.

Even though this chemical combustion is the process upon which a great deal of the production of the world's energy is based, since carbon is an essential element in coal, wood, oil and petrol, yet the development of energy, when seen through the eyes of the atomic physicist, is exceedingly modest. For each atom of carbon that is burnt the development of energy is only about 4 electron-volts, which is of the same quantitative order as the cohesive energy of the electrons in the outer part of the atoms; and this is what we might expect, as the chemical properties conditioning the combustion are determined by these same outer electrons in the atom. If the combustion of carbon can still in actual practice yield a serviceable output of energy, this is due to the fact that *all* the atoms in the piece of coal consumed generally enter into the combustion.

If we now attempted to exploit atomic energy by making protons and neutrons combine together, we should obtain for each nucleus large values of quite another order, for the attractive forces between these particles are vastly greater than the attraction between the atoms. In the formation of a helium nucleus of two protons and two neutrons, for example, an energy of no less than 28 million volts would be liberated; and it is therefore tempting to ask oneself whether it would be possible to build up atomic nuclei by way of such a "burning up" of elementary particles.

We must first examine the question whether the "fuel"—that is, the protons and neutrons—is to be had in sufficient quantities. As for the protons, that is easy enough, for we need only buy a bottle of hydrogen. On the other hand, the undertaking is wrecked by the fact that for the neutrons very much the same thing holds good as for the positrons—namely, that free neutrons are of their own accord captured by atomic nuclei, cohesive energy being set free, and un-

fortunately this happens in spite of any human check. Even though the neutrons make up over half the weight of the whole world, they do not exist in nature as free particles, but can be obtained only through experiments in nuclear explosion, and therefore by the consumption of that very energy which we are seeking means to obtain. This would therefore mean that all the carbon on the earth would have had to be already burnt up into carbon dioxide. So that this method also is excluded, through lack of material for fuel.

But we have not altogether lost heart, for even if we cannot build the nuclei up directly from their separate parts, we can still entertain the possibility of obtaining energy by building up heavier nuclei from lighter ones; or, to use more general terms, by building up nuclei having great cohesive energy by utilizing nuclei having lower cohesive energy.

We have already met with an example of such a process, whereby α-particles with great kinetic energy are formed; this was the splitting up of lithium into α-particles through bombardment with protons, which was carried out by Cockcroft and Walton:

$$^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} = {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

This process was indeed characterized by the great development of energy of 17 million volts. We repeat the calculation of energy with the exact atomic weights, which are, for hydrogen 1·00813, for helium 4·00389, and for lithium 7·01818. The loss of mass in the process then becomes 0·01853, which, multiplied by the celebrated 931 (see page 172), gives the energy as 17·25 million volts. The gain in energy at each splitting is therefore 17·25 million volts, less the kinetic energy of the few hundred thousand volts which the protons brought with them. The splitting up of lithium is always one of the processes whereby the greatest release of energy is won, and therefore in the following argument we will restrict ourselves to this process.

The problem now is, whether there is a possibility of making an apparatus from which we can get energy on a great scale by making the hydrogen and the lithium nuclei react on one another, forming helium nuclei. It is evident beforehand that, in spite of the great development of energy at each separate explosion of the atom, we do not really gain energy through Cockcroft and Walton's experiment, for the probability of striking the lithium nuclei is so small that only one proton among hundreds of thousands gives rise to a nuclear explosion. If we are to succeed in utilizing the energy of the explosion, we must somehow use the energy set free at each single explosion of the atom to bring about new nuclear explosions of other lithium atoms.

In other words, we have to take as our goal the same state of things as obtains when carbon is burnt up. We know that a bucket of coal does not begin burning of itself, even when it is exposed to the oxygen of the air, but that combustion commences only when one of the lumps of coal is kindled; that is to say, heated up to a certain ignition temperature. Once the burning process has started, the energy developed by the combustion will make adjacent lumps of coal reach the ignition temperature and begin to burn. In accordance with the views on the nature of heat discussed in the Introduction, the ignition temperature for a lump of coal is no more than that temperature at which the oxygen and carbon atoms have enough kinetic energy to come so near to one another through reciprocal collisions that the forces of attraction between the atoms bring about the chemical reaction.

We might therefore conceive some notion of carrying out the same "nuclear chemical" reaction by filling a container with lithium and hydrogen, and "kindling" this mixture by sending so many high-speed protons into it that one lithium atom was broken up into two high-speed α-particles. We could now give our fantasy fuller play, and imagine that the

α-particles, through collision, might give so much energy to some of the hydrogen nuclei that these latter would be able to bring about new nuclear transformations, whereby the process would spread more and more rapidly, until all the lithium present had been transformed, and we had developed gigantic amounts of energy.

There is only one thing wrong about this calculation, and that is, that both the α-particles and the protons, under normal conditions, are much more likely to give up their energy to the outer electrons of the atoms than to transfer this energy to the atomic nuclei, so that the greater part of these particles will have lost their energy through ionizing the atoms before they succeed in striking a nucleus. This basic circumstance is revealed by any cloud-chamber photograph of α-particles (see Fig. 2), where we see that the great majority of α-particles are brought to a stop without colliding with any atomic nucleus.

It seems, therefore, rather impossible under normal conditions to make the reaction transmit itself of its own accord to other nuclei. While a chemical process like the combustion of coal has no difficulty in propagating itself, since the atoms lie close together, with no space between them worth mentioning, the main cause for the failure of the nuclear combustion is that the nuclei, under normal conditions, are sheltered against their surroundings by the electronic systems. Since the surface of the nuclei is only about 10^{-12} cm., while that of the atoms is about 10^{-8} cm., which is 10,000 times as great, the electronic system around an atomic nucleus fills a volume which is $10^4 \times 10^4 \times 10^4 = 10^{12}$ times as great as the volume of the nucleus itself. It is, however, only the nuclei that enter into "nuclear combustion," and the electrons merely spoil the game by immediately swallowing up the energy produced. The situation can therefore be roughly compared with what would arise if we blended a litre of coal-dust uniformly with a milliard cubic

metres of sand, and tried to make the mixture burn by setting fire to one corner of this cubic kilometre. Anyone will at once see the hopelessness of the undertaking.

The considerations we have just put forward hold good, however, only for nuclear transformations where it is only charged particles that are emitted. If on the other hand there existed energy-producing processes which were set up by neutrons, fresh neutrons also being set free at the same time with the power to carry the process on further, then we might catch a glimpse of the possibility of extracting the nuclear energy. In contrast to charged particles, such as the α-particles in the lithium process, neutrons do not essentially lose any kinetic energy on going through matter, nor moreover do they demand any energy to speak of for penetrating into a nucleus and bringing about a transformation.

As a matter of fact, it is only a short while since such nuclear processes have indeed been found, which moreover were accompanied by a development of energy ten times as great as in the lithium process, and this has led to a renewed discussion on nuclear energy. The honour of this great discovery belongs first to the German chemist Hahn and his fellow-workers. Hahn was at work on a problem which for many years had been worrying both physicists and chemists, the problem, namely, of what elementary changes come about when we bombard the last substance in the series of the elements, that is, the substance uranium, with neutrons. It had already been found that, when an irradiation like this is carried out, a regular jumble of artificially radio-active substances was formed, the placing of which in the periodic system had given rise to a good deal of discussion. For a long time it was believed that these puzzling substances must be put after uranium in the series of elements, thus having an atomic number over 92. At the beginning of 1939 Hahn was able by careful chemical analyses to state that among these puzzling substances there was a radio-active barium isotope,

that is to say, an element lying far away in the series of elements from the starting substance uranium. In contrast with all changes hitherto known in the elements, where the atomic number and atomic weight of the element formed were always separated only by a few units from the substance we started with, we now for the first time clearly had before us a process which can truly be held to deserve to be called splitting the atom. Further chemical investigations by Hahn now showed that the uranium nucleus when bombarded by neutrons was split into two more or less equal parts, which must probably be given by the equation:

$$92^{U} + 0^{n} = 38^{Sr} + 54^{Xe}$$

Later investigations have, however, made it likely that the splitting of uranium, which on the analogy of the processes of splitting the cell in biology was often called *uranium fission*, need not always come about in this way, but can happen too in several other ways, in which the uranium nucleus was split into two more or less equally heavy nuclei.

But also physicists now began to take an interest in the process, since from a physical standpoint it seemed highly remarkable that such great effects could be caused by one small neutron, and particularly that the fission should be found showing itself to great effect with slow neutrons also. Theoretical considerations on the cohesive energy of the nuclei concerned led to the result that we must expect to find that uranium fission is accompanied by an enormous development of energy. Frisch in Austria was the first to succeed in showing this energy and measuring it experimentally, the energy making itself known by the two newly found nuclei being hurled apart with an energy of altogether 200 million electron-volts. This is the highest production of energy that has ever been seen in one single nuclear process, so that we can understand that the problem of the development of nuclear energy took on a new actuality. Furthermore, it was

very soon shown that in uranium fission neutrons are also set free, so that the conditions given above for carrying the process further seemed to be present.

But it must not be thought that the solution of the problem is henceforth in our hands: there are still many details in the fission process that have to be more closely studied before we can make any definitive statement as to how far in practice the obtaining of the nuclear energy along these lines is possible. Anyhow it would seem to be necessary to have great quantities of pure uranium at our disposal if we are to get the energy in this way, and, what is worse, great quantities of the rarer of the two isotopes found in uranium; for the rarer isotope has shown itself to be by far the most active in uranium fission. The risk is, therefore, that we must first of all apply great quantities of energy to separate the uranium isotopes, and so the question is, whether it is worth it. But even if the obtaining of atomic energy on this earth is always an open question, there is much which suggests that in other places in the universe—*within the stars*, that is to say—conditions are such that a development of energy through the reactions of atomic nuclei can occur on a gigantic scale. It is, of course, impossible to make measurements of the physical conditions obtaining inside the stars, but the astrophysicists, by methods which we cannot examine here, have been able to measure the mass and volume of the stars, and also the energy which they send forth into space in a given interval of time. Observations of stars in different stages of development have led to the view that a star, during its unbroken radiation of energy over vast periods of time, must always be shrinking more and more, such shrinking being accompanied by a development of energy. Exact calculation, however, shows that this shrinkage is not enough to give rise to the immense amounts of energy which are radiated by a star. To take one example: the sun, owing to the radiation which has been proceeding during its lifetime, would long ago have cooled down if there

did not exist other sources for producing energy besides its shrinking.

Many astrophysicists are therefore now inclined to believe that the hidden production of energy comes in reality from nuclear reactions of a different kind, in which atomic nuclei with low cohesive energy are changed into nuclei with a higher cohesive energy. These processes are not thought of as having their seat everywhere within the star, but only in a limited field around the star's centre, where there must be assumed to prevail such immensely high temperatures and pressures that nuclear reactions become possible on a great scale. While the temperature at a star's surface has been ascertained by measurement to be some thousands of degrees, we can find by calculation that in the centre of the stars there may be temperatures of several million degrees and pressures of many million atmospheres. Temperatures such as these mean that all the atoms have an enormous kinetic energy, so that in their collisions with one another they have a great probability of giving rise to nuclear reactions. This probability is further strengthened by the high pressures, one result of which is that the particles are given frequent opportunities of colliding with one another.

There is thus every possible reason to stress the fact that a winning of atomic nuclear energy on a great scale is not a physical impossibility, but that it can be realized only under such extreme conditions as we can hardly hope to secure on this earth of ours. The highest temperature that has been successfully produced in the laboratory so far is about 4,000 degrees centigrade, so that we have a long way to go before we attain the stars' millions of degrees, which we have to assume are necessary if we are to reach the "ignition temperature" for the nuclear processes. And even if we succeeded in reaching such high temperatures, we should be brought up against the insuperable difficulty that we should not have any material for constructing our apparatus, inasmuch as any

substance would immediately evaporate at these temperatures.

But it is rather curious to reflect that a great part of that energy which the earth is receiving and has received from the sun, on which we are able to draw by exploiting coal-measures, waterfalls, and so on, and which is likewise the condition for the persistence of life itself, in all probability owes its birth to the winning of this much-discussed atomic nuclear energy in Nature's mighty laboratory.

Conclusion

We have now followed the development of atomic physics over a full generation, from the very first discoveries, to give us some insight into the world of the atoms, down to the epoch-making exploration in recent years of the interior of the atomic nuclei.

This swift development has been made possible only through the fact that a great number of scientific men have devoted their lives to the investigation of these problems, so fundamental for the understanding of nature. We have sought to show how important for this development have been the mutual action and collaboration between experimental and purely theoretical research. But it has not, of course, been possible to set forth all the many meticulous inquiries on which all these discoveries and advances were based, and which have enabled them to be continued. We have had to limit ourselves to discussing those labours which must be described as pioneer work, and to giving the names of investigators which will for all time be linked with these so eventful years in the history of physics. But we must also lay stress on the great importance of the supplementary work of an army of less well-known men of science, to whose lot it never fell to make the greatest discoveries of all, but who pursue their unswerving way, steadily improving methods and bettering results.

Further, for the sake of the truth it must be said that in the history of atomic physics we have also to see false reasoning and mistakes, for in science we often have to feel our way experimentally. But such mistakes have not, as a rule, been allowed to stand very long, for there were always plenty of investigators ready to test and criticize new discoveries and theories. Such episodes as these in the history of physics have

not been included in this account, and for this reason we may not have given an adequate impression of the difficulties that have had to be overcome. But it is true of all natural science, and especially of physics, that it can never fall into such lasting mistakes as we find in other fields of intellectual life, since physics is concerned with the unchanging laws of nature, which have their being independently of human activity. It is this fact which will always ensure for natural science a body of active worshippers and enthusiastic followers.

Although in this account we have laid the main emphasis on pure natural science, and on the interaction between theory and experiment, yet we have also on occasion pointed to the interaction between physics and technology, which many people regard as the essential thing, owing to the material blessings which it brings to mankind. It need hardly be repeated here that classical physics constitutes an essential part of the foundations on which the highly developed technology of our day is based. Modern atomic physics, on the contrary, is so young that technology has not as yet exploited its results to the full. At the same time, a long series of practical applications can be named, as, for instance, the application in medical science of the Roentgen rays and the radio-active substances, the use of the electrons in radio, television and sound films, and, among the latest discoveries, the use of the artificial radio-active substances in biology and medical science. This is, however, only one aspect of the interaction between physics and technology. The other side is seen in the fact that technology is often in a position to offer the physicists improved means of solving their problems. We get a lively idea of this by reading old reports on physical investigations, from which we can see that very often a man had with great difficulty to make for himself the measuring instruments and other appliances which in our own day can be bought far more cheaply and of very much better quality.

Technology has in this way paid heavy instalments of the debt which it owes to physics.

Owing to its position as the foundation of technology, physics is an important member in the modern social organism. But there are grounds for stressing the fact that the development of physics is not furthered by making exclusive demands for such results as can at once be applied in practice. On the contrary, it is often the case that those results of research which seem to be farthest removed from the needs of practical life, show themselves in the long run to be of the greatest importance in respect of their technical applications. Therefore we shall do both physics and technology the best service by allowing the physicists to work along their own paths, which are determined wholly by the urge to attain to greater knowledge of the wonderful laws and the rich life that govern and penetrate even what is called lifeless nature.

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