ATOMIC ENERGY

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being
THE NORMAN WAIT HARRIS LECTURES
delivered at NORTHWESTERN UNIVERSITY

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PREFACE

By its gracious invitation to deliver a series of Norman Wait Harris lectures in 1947, Northwestern University gave me the incentive and the opportunity to present the science of atomic energy—as much of it as could go into four hours of lecturing time—to an audience of laymen. One hesitates to use the word "layman" lest it be taken as having a derogatory flavor; but all I intend to imply is that the audience consisted largely of people whose special fields of interest were other than physics. Desirous of spreading the influence of its lectures beyond the confines of its auditorium, Northwestern University has prescribed that the Norman Wait Harris lectures be published; and here this series stands in print, changed only in minor phrases from what was spoken on the platform. The professional physicist, if any such person reads these pages, will probably feel that much more information could have been packed into the space allotted. So it might have been; but the object was not to see how much could be squeezed into four hours, it was to develop and stress and reiterate the salient features of the subject, introducing little that might divert the reader into bypaths, however fascinating. He will not, I conjecture, fail to "see the wood for the trees." Definitely this is not a treatise on nuclear physics, but a narrative of the basic facts most pertinent to the transformation of energy of rest mass into energy of motion and energy of heat, which is what we mean when we speak of "atomic energy." There is indeed a good deal about radioactivity, but only so much as seems essential to an understanding of that transformation and of the functions of the pile. I have been chary of predictions: the future will tell us what now we can only guess. What has already been done is more than sufficient to make the topic of this book one of the monumental achievements of this time—or any time.

K. K. D.

New York, N. Y.
June, 1948

ACKNOWLEDGMENTS

Since their names along with nearly all others have been omitted from the pages which follow, it becomes doubly the author's duty to give credit to the physicists who have provided him with the originals of the photographs, representing their results or their equipment, which decorate the pages of this book: P. M. S. Blackett of Manchester University (Figure 11), P. I. Dee of Glasgow University (Figures 6, 7, and 10), and M. A. Tuve of the Carnegie Institution of Washington (Figure 5). The pictures from Messrs. Blackett and Dee appeared first in the *Proceedings of the Royal Society of London.*

CONTENTS

THIRTY-FOUR years ago I had the privilege of hearing, as Norman Wait Harris Lecturer of 1913, a very distinguished physicist. This was Joseph Ames, professor in Johns Hopkins University. Later he was to become the Chairman of the National Advisory Committee for Aeronautics, and an airfield in California perpetuates his name. With him I now share the honor of being invited to speak about physics by the Norman Wait Harris Foundation. There is little else that I share with my predecessor, for in these thirty-four years our science has been transformed. If there is anyone here who remembers all that Ames said, he must not hope and he need not fear that he is going to hear the same things over again. Most of what I shall say was unknown in 1913, that last year of the old dispensation before the world wars broke upon us. The listeners were unwittingly taking their leave of the era to which they were born; but Ames was leading them across the threshold of a marvelous new building, the edifice of the new physics. At that time neither Ames nor anyone else had pressed very far beyond the threshold, and nobody could divine the plan, the spaciousness, and the fantastic contents of the mansion. The plan was found to be grandiose, the spaciousness immense, the contents fascinating altogether and beneficent in the main. Some, however, of the contents have proved to be very terrible; and this, I daresay, is one of the reasons why at this time the Foundation chose physics for the topic of these lectures.

This brings out one of the contrasts between Ames' position and mine. The house of physics, in 1913, was a stable and a friendly house. We all lived in that house; it included both the world of everyday nature around us and the tools with which technology had been providing us. We were like tenants in a sturdy old-fashioned apartment house which somebody else had put up. We accepted the foundations and the structure, the roof, the heating and the lighting, quite as a matter of course—not that we always thought them convenient, but we did think them completely reliable and perfectly durable. Ames took his audience of 1913 on a conducted tour of their physical home, and I think that they emerged from the tour with the feeling that all things were sound and solid, and stable with a stability matching that of the political system under which they lived.

Now we are in 1947, and the house has become very strange. It is much grander than ever before, and together with its annex, the house of technology, it is much fuller of streamlined gadgets; but it is of a modernistic style which has a freakish look to all but those who built it and those who were bred to it, and we have the uneasy feeling that there is a high explosive lurking somewhere near the furnace. The tour takes on a practical importance when the tenant becomes aware that one of the recesses of the mansion is inhabited by something of demonic power. Ignorance is not safe when the unknown may not be friendly; and, since we discovered that matter is not invariably stable, the known has become so awesome as to suggest that the unknown can be unfriendly.

In speaking of the instability of matter, I do not want to scare you by implying that this world or any substantial part of it is suddenly going to vanish. This would be a very far-fetched worry, to be recommended only to those who have nothing else to worry about and feel that they need something worrisome. It is, however, a fact that during the last few decades the physicist has come to realize that matter is not quite permanent. Matter is capable, indeed, not of vanishing into nothingness, but of turning into something new and strange and fiery. In the language of the ancients we might say that, under certain circumstances, earth is capable of turning into fire.

There are several crucial dates in the course of this realization. With the advantages of hindsight, we know that some of them, and not the least significant, occurred even before 1913. The two most recent of the crucial dates are in December 1938 and July 1945.

The significance of December 1938 is that, some time in that month, certain physicists abroad corrected a fortunate mistake which had thus far prevented everyone from realizing that ever since 1933 we had been provoking "the fission of uranium." This is a process involving the conversion of matter in great quantities into something else than matter. People were doing it all over the world without knowing just what they were doing. You may have guessed why I call it a fortunate mistake: if not, it will become clear.

The significance of July 16, 1945, is known to everyone, and I mention it only for the record. Just before dawn of that day, a so-called atomic bomb exploded in the desert of New Mexico. Not many people witnessed the explosion, and even they did not really see it. Those who were ten miles away had been commanded to lie down with their feet toward the blast and their faces turned to the earth. Those who were twenty miles off had been ordered to stand with their backs to the explosion. All of them, though looking down to the ground or straight away from the bomb, were wearing the darkest of dark glasses. Nevertheless it was an awful experience, in the true sense of that much misused word. Those who were looking toward the distant mountains saw them illumined with light much more brilliant than sunlight, which shone on and on until, as one of the witnesses told me, "one wanted it to stop." In due time, of course, the roar of the explosion arrived with the more modest speed of sound. Some people were so awed by the spectacle that they do not remember having heard the noise; others were so excited that they did not know what it was. Afterwards came the colossal clouds of swirling and turbulent smoke, which have been shown in the movies, and which recall the words of the Dies Irae, *"Solvet saeclum in favilla."* A military policeman is said to have shouted, "My God, it's got away from the longhairs!"

Well, it *had* got away from, let us say, the scientists; but not in the sense that the policeman intended. The scientists foresaw pretty accurately what was going to happen. No sudden advance in scientific knowledge came about because the bomb went off. But the scientists also foresaw that as soon as the bomb should go off, "atomic energy" would cease to be theirs to do with as they pleased and would forthwith become something of the gravest concern to the makers of the highest national and the highest international policies. It was not the scientists who chose where and when the next two bombs should be exploded. It appears that these brought peace, so that the instability of matter had a tranquilizing effect upon the instability of the political world. If the bombs also lead to the formation of a workable league of nations, the instability of matter will have brought about the stability of the political world, than which no more delightful paradox can be imagined. The brilliant light over the sands of New Mexico which blotted out the morning stars may itself have been the morning star of perpetual peace. But now I am getting out of my depth and will beat a hasty retreat to waters where I can stand upon the foundations of physics.

You are to hear of some concepts not easy to believe in. You will hear of atoms so small that it takes a hundred millions of them, laid side by side, to extend over a linear inch; and of nuclei so much smaller yet that, if we could lay them side by side (which we cannot do), it would take a hundred thousand of them to span the diameter of one atom. What is even more astonishing, you will hear precise assertions made about the structures of these tiny bodies. You will hear that they circle and spin and that they make collisions with each other of which the consequences are described as closely as though we had before us the report of a traffic accident. These and other statements will defy your notion of the solidity of solid matter and the deadness of dead weight. It will occur to you to wonder whether these atoms and these nuclei and these gyrations are really real or only figments of the physicists' imaginations.

If anyone be minded to ask such questions, I here and now refer him to the specialists; not, however, to the specialists in physics, but to another kind. The word "real," the word "really," the word "reality," these are three very difficult and tricky words. The persons whose business it is to define them are the philosophers. Therefore, anyone who wants to know whether an atom is real or a nucleus is real or an electron is real is advised to take his question to the Department of Philosophy of this University. All *I* claim is that, by making these postulates, the physicists and chemists have been able to discover atomic energy and invent atomic bombs and also to discover and invent many other things not sinister at all; and they are still going very strong. This is what I think is called the pragmatic test: our ideas work, and how! Someone may contend that the physicists might have started from totally different postulates and could still have arrived at atomic energy and all the rest. If anyone wishes to make such a contention, I will not dispute him. I will merely point out that the burden of proof is on him, and I think he will not find it an easy burden to sustain. Without further apologia I now proceed to the foundations of physics.

You are to consider the material world as made up of an incredibly enormous number of atoms incredibly small. The word "atom" may bring back to you the names of Democritus and Lucretius, those distant figures who are often described as the founders of atomic theory. We will make them a perfunctory bow and pass rapidly on, for their primitive atoms bear about as much relation to ours as do the pebbles on the beach to the delicate wheels and springs which are contrived to fit their places and perform their functions in a watch. The word "atom" may also recall to you that in Greek it means "indivisible." Once when Lord Kelvin was inveighing against the practice of inventing divisible atoms, a young man in the company remarked, "There you see the disadvantage of knowing Greek." This disadvantage is growing to be so rare that now you seldom find anyone bothered by our modern atoms equipped with parts and structures.

These countless atoms are of a relatively few different kinds, certainly fewer than a thousand.* All of them belong to the various chemical elements. The elements are only ninety-six in number, so that there are several kinds of atom to an element: we shall see the distinction later.

Some of the elements are known to everyone: copper, gold, and silver, for example. Some are known to every literate person: hydrogen and oxygen and carbon, for example, and now uranium. Many more become known to students of ele-

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* Since the delivery of these lectures this statement begins to seem an underestimate.

mentary chemistry, and of course there are some that are curiosities even to the chemist. We have good reason to believe that the ninety-six we know are nearly all there are. It is pretty certain that we shall never discover another, though we might bring two or three into a transient existence. The thousand or so kinds of atoms of the hundred or so elements are, therefore, all the building blocks of the material universe.

Every atom is a sort of miniature of the solar system, composed of a central sun surrounded by revolving planets. This is a simile which has been used unnumbered times, but no one to my knowledge has thought of any other, except Sir William Bragg who compared the atom to a man's head with a cloud of mosquitoes buzzing around it. This is a disagreeable simile even in February, and will be more so if you remember it in June. We will, therefore, employ the solar system as our image.

Of course, there are some differences between the solar system and the atom. For example, there is the item of scale. The solar system is four billion miles across; four billion atoms laid side by side would extend over only a few inches. More fundamental is the fact that the force which binds the planets to the sun is gravity, whereas in the atom the corresponding force is electrical. The planets of the atom are *electrons,* each bearing a *negative* electric charge. The central sun of the atom is—and here comes one of the most important words in physics—what we call the *nucleus.* The nucleus has a *positive* electric charge. In electricity, positive attracts negative. By its positive charge the nucleus attracts the electrons and keeps them in their orbits. Gravity no doubt is down there too, but insignificant in its strength compared to the potent electrical forces.

The atom, then, is a miniature solar system in which electronic planets revolve in orbits around the nuclear sun, being attracted electrically to the positive charge on that sun. This table, this floor, this earth, solid and dense as they seem, are galaxies of these nuclei and these electrons, whirling and whizzing and bumping around. I concede that this is difficult to swallow, and I can readily put myself in the layman's position and regard it all as very weird. However, I have already indicated what you can do about it. If you don't like these postulates, start from those you prefer and deduce as much as the physicists have deduced. When you succeed, the King of Sweden will be waiting for you in Stockholm with your Nobel prize in his hand.

Were I lecturing on chemistry or on ordinary physics, I should be spending nearly all my time in talking about these electronic planets and their orbits. All chemical phenomena arise from them, and chemical energy in particular. When you burn coal, the carbon atoms of the coal and the oxygen atoms of the air join together, and the ensuing rearrangement of the joint electronic family provides the light and heat. When you provide yourself with energy by eating a beefsteak or nibbling a chocolate bar, something of the same sort happens, much more complicated. When someone detonates a bomb of TNT something of the same sort happens, very quickly and therefore very violently. But when the atomic bomb goes off, nothing of the sort is responsible. When the atomic bomb goes off, it is because something is happening in the *nuclei.*

Why then do we not speak of the *nuclear* bomb and of *nuclear* energy? Well, we ought to, and the fact that we do not is a linguistic disaster. I do not know who is to blame for the disaster, but it happened on the day of Hiroshima. Somebody wrote of an atomic bomb, and the usage spread like wildfire, or, to modernize my image, it spread like the chain reaction. It is too late to mend our ways, excepting in the private conclaves of the scientists. But if you are going to remember only one thing from this lecture, I beg of you let it be this: the term "atomic energy" is a boner, and such a boner as would get a very black mark from any conscientious professor of chemistry or physics. If that term properly means anything, it means the chemical energy such as we get by burning the coal and digesting the beefsteak. What is miscalled atomic energy comes from the nucleus and is many millions of times as great.

Why then did I bring in the planetary electrons, since it is the nucleus which is my theme? This is because they tell us something about the nucleus which it is essential to know: to wit, the nuclear *charge*. This last in fact is equal to the sum of the charges of the electrons. So, we just have to count the electron family and multiply its number by the charge of the individual electron. We denote the number of electrons by Z and the charge of the individual electron by e, and we put on a plus sign to remind ourselves that the charge of the nucleus is positive. So, the nuclear charge is $+Ze$; this is also an instance of our preference for using symbols rather than words.

We are indeed able to count the electron family, though not, alas, by the impossible expedient of looking at the atom with some super-microscope in which the electrons are visible. I should enjoy explaining the several ways, confirming one another, in which the count is made; but if we entered that forest we should probably stay in it till the time for these lectures is over, and we must not spend on auxiliary matters the time which is needed for the fundamentals. Take it, therefore, on faith, when I say that to each of the ninety-six elements corresponds some integer between 1 and 96 (both numbers inclusive), this being the number of its planetary electrons. Or, to turn the statement around: to each of the integers from 1 to 96 there corresponds one of the elements having just that number of electrons revolving as planets around each of its nuclei. Anyone with his memory properly trained can shout "hydrogen" as soon as you say "one," or "uranium" when you say 92, or "gadolinium" when you say 64.

Since Nature has numbered the elements in this way, we arrange them in the order of their integers, and this arrangement is what is called the Periodic Table of the Elements, though the reason why it is called "periodic" pertains to the electrons and I will not take the time to explain it. You divine, now, why we feel so sure that we have discovered practically all the elements. There couldn't be an unknown element between 1 and 96, for if there were such a one it would have to have a fractional number of electrons, and electrons do not come in fractions. This would not prevent us from finding 97 and 98 and so on, and that is why I left a loophole. But an atom with, say, 100 electrons would require a nucleus with a charge $+100e$; and there is reason to believe that such a nucleus would not be stable even for an instant, if we could manage to put it together. Incidentally there is also a nucleus of zero charge; we shall have a great deal to do with it, but its entry can be postponed a few minutes.

TABLE I

THE ELEMENTS

1. Hydrogen (H)
2. Helium (He)
3. Lithium (Li)
4. Beryllium
5. Boron
6. Carbon
7. Nitrogen (N)
8. Oxygen (O)
9. Fluorine
10. Neon
11. Sodium
12. Magnesium
13. Aluminum
14. Silicon
15. Phosphorus
16. Sulphur
17. Chlorine
18. Argon
19. Potassium
20. Calcium
21. Scandium
22. Titanium
23. Vanadium
24. Chromium
25. Manganese
26. Iron
27. Cobalt
28. Nickel
29. Copper
30. Zinc
31. Gallium
32. Germanium
33. Arsenic
34. Selenium
35. Bromine
36. Krypton
37. Rubidium
38. Strontium
39. Yttrium
40. Zirconium
41. Columbium
42. Molybdenum
43. Technetium
44. Ruthenium
45. Rhodium
46. Palladium
47. Silver
48. Cadmium
49. Indium
50. Tin
51. Antimony
52. Tellurium
53. Iodine
54. Xenon
55. Cesium
56. Barium
57. Lanthanum
58. Cerium
59. Praseodymium
60. Neodymium
61. Prometheum
62. Samarium
63. Europium
64. Gadolinium
65. Terbium
66. Dysprosium
67. Holmium
68. Erbium
69. Thulium
70. Ytterbium
71. Lutecium
72. Hafnium
73. Tantalum
74. Tungsten
75. Rhenium
76. Osmium
77. Iridium
78. Platinum
79. Gold
80. Mercury
81. Thallium
82. Lead (Pb)
83. Bismuth
84. Polonium (Po)
85. Astatine
86. Emanation
87. Francium
88. Radium
89. Actinium
90. Thorium
91. Protactinium
92. Uranium (U)
93. Neptunium (Np)
94. Plutonium (Pu)
95. Americium
96. Curium

The Periodic Table of the Elements is exhibited on page 11. The names of the elements usually have to be abbreviated, and a very few of the abbreviations are shown in the table. I will repeat the names of the first eight. They are *hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen,* and *oxygen.*

Of these eight, *hydrogen* at ordinary temperatures is a gas and a very explosive one, which in combination with oxygen makes up all the water in the world. *Helium* is also a gas but a very inert one, which is used as the filling for dirigible balloons in order to avoid the risk of explosive hydrogen. *Lithium* is a very reactive metal whose chemical properties prevent us from using it for structural purposes. *Beryllium* is a metal not nearly so reactive, available for use in alloys when extreme lightness is desirable. *Boron* is not a metal at all, but a solid insulator. *Carbon* is what we burn in the coal furnace and is an essential part of nearly all we eat. *Nitrogen* is a gas which is useless to us when we breathe it, but of extraordinary and many-sided value in the chemistry which we use and in the more intimate chemistry of the body by which we live. Oxygen is the vital element *par excellence:* if we fail to supply it constantly to the coal fire and to ourselves, the fire and we are extinguished.

You may wonder what all these facts have to do with the nucleus. The answer is that they have only a distant connection with the nucleus. I put them in so that the names of the elements might have some associations for you, even though the associations be irrelevant. To speak more carefully, the nucleus does exert a sort of remote control over these chemical properties, with the emphasis on *remote.* The chemical properties are the business of the planetary electrons. The nucleus minds its own business; but one of its duties is to fix the number of the planetary electrons and keep the family together, and that is where its remote control comes in. It is rather wonderful to think that we have correlated all that immense variety of chemical properties, with nothing but different values of a single integer number—the number of electrons in the atom, the number of positive charges on the nucleus. However, we must now turn to the second main duty of the nucleus, which is to provide *mass* for the atom.

Mass and *weight* are two properties between which the physicists draw a sharp and subtle distinction, which is a hard nut for the elementary student to crack. I spare you trouble, at some cost to my conscience, by allowing you to confuse weight and mass. The next thing to be said is that, just as in the solar system the sun is heavier by far than all the planets put together, so in the atomic system the nucleus is heavier by far than all the electrons put together. In all atoms but one, the nucleus outweighs by more than 3700-fold its whole electron family; in the one exceptional case the ratio is 1850. The electrons are the nimble, lightweight, agile, animated parts of the atomic economy. The nucleus is the heavy, dull, and sluggish part. But there is a proverb warning us to beware of the wrath of the complacent man; and devastation overseas has now borne witness to the fury of the nucleus when its equanimity is disturbed.

Before giving you some precise figures on nuclear masses, I must talk for a while about units. Units are a dry subject, so I permit myself to use a wet illustration.

As everyone more or less knows, there are some things for which there are natural units and others for which the units have to be conventional. Thus, suppose that I am giving a recipe for eggnog to a friend. It will do him little good if I say that he must take one of milk, one of cream, one of rye whiskey, and one of rum. Milk and cream and rye and rum are measured in conventional units, and there happen to be several of these. On the other hand, when I go on to the egg part of the drink, it will be adequate to tell my friend that he must use *twelve of egg*. The grammar will sound somewhat odd, but it will not obscure the essential point that *egg* is something of which there is a natural unit and *milk* is something of which there is not.

While I was introducing the nuclear charges, I was able to dodge the issue of units because *charge* is like *egg* in that it has a natural unit. The natural unit of charge is the electron charge. Charge in fact out-eggs egg, because all electron charges are equal and all are indivisible. There are, indeed, conventional units of charge, in terms of which I might express the electron charge. However, it will be of little use to anyone to learn how many electron charges it takes to make up one conventional unit, unless he is a person accustomed to measuring electric charges in conventional units. Such a person would be a physicist or an electrical engineer and would know how to look up the figure in question. I therefore continue to express all charges as multiples of the electron charge *e*.

Mass, however, is more like *milk.* There is no natural unit of mass, but only a variety of conventional units. Moreover, there are some of these units with which everyone is acquainted: we all have a notion of the feel, that is to say of the heaviness, of a one-ounce letter, a one-pound box of candy, or a twenty-five-pound suitcase. It may seem that I ought to give you the masses of the nuclei in ounces or pounds, or in grams so as to favor the metric system. But here enters another aspect, that of the *suitability* of the unit. If you were to go into a dairy and ask for five ten-thousandths of a ton of butter, nobody could deny that you were explicit, and yet there would be a feeling that you had chosen an unsuitable unit. If I were to give you the masses of the nuclei in terms of ounces or grams, my remarks would be studded with septillionths, since it takes about a septillion atoms to make up one gram of an element. Clearly the gram is not a suitable unit. We want an appropriate one. For most purposes—not for quite all—the best way to get a unit of appropriate size is to adopt the mass of some particular kind of nucleus or atom as our unit.

In Table II appear the masses of the atoms of the eight lightest elements, the elements which I mentioned earlier by name. They are in terms of a particular and suitable unit; from this table it is possible to guess just what the unit is. There is just one atom here for which there are zeroes and nothing but zeroes to the right of the decimal point. That is an atom of oxygen, and it is our standard. Our conventional unit of mass—I am surprised to have to admit that it has no

TABLE II

THE STABLE ISOTOPES OF THE FIRST EIGHT ELEMENTS

1. H(ydrogen)	1.0081	2.0147	
2. He(lium)	3.0170	4.0038	
3. Li(thium)	6.017	7.018	
4. Be(ryllium)	9.015		
5. B(oron)	10.016	11.013	
6. C(arbon)	12.004	13.008	
7. N(itrogen)	14.008	15.005	
8. O(xygen)	16.000	17.005	18.004

better name than "mass unit"—is one-sixteenth of the mass of that atom.

In certain circumstances, and in one very important circumstance indeed, it *is* valuable to be able to express nuclear masses in grams. I therefore give you the measure, in grams, of this mass unit of ours. This measure is

$$\text{One mass unit} = 1.65 \times 10^{-24} \text{ gram}$$

which is to say, it takes six hundred thousand millions of millions of millions of these mass units to make up one gram, the twenty-eighth part of an ounce. There is no use in trying to visualize such a number. The words impart a momentary awe, and when it subsides one goes on with the argument.

Now there comes up for comment the fact that for each element two or more masses are given in Table II instead of only one. This is a consequence of something I mentioned earlier, to wit, the fact that there are many more kinds of atom than there are of elements, and on the average there are several kinds of atom to each element.

The different kinds of atom belonging to one and the same element have nuclei identical in charge but different in mass. They are called "isotopes" of the element or "isotopes" of one another. This is a technical word which you must remember. It was contrived by combining Greek roots to signify "in the same place." Two or more isotopes of one and the same element are, in fact, roommates in one and the same place in the Periodic Table.

This word and this idea came into science in 1907 by way of radioctivity. However, what concerns us now is the proof that a single element may have atoms of various masses. This proof was not made until 1913. Earlier it had been assumed, almost universally, that all atoms of a single element must be exactly alike in every way. This was an example of an over-simplified assumption, which worked perfectly well for a while and then had to be modified for taking account of new knowledge. Some of the assumptions that I am making here belong to the same class. This last remark is what is called a "hedge." I am hedging in order to protect myself against someone who may glance at the printed version of these words hereafter, at a time when some, at least, of today's assumptions may have gone "the way of all flesh." The way of all flesh, for atomic and nuclear theory, is to get steadily more and more complex as the new facts pour in. Some perfectionist may think I ought to do a thorough job of hedging by making my assumptions so complex that they will be able to take care of all new facts as fast as these are discovered. Such a policy would have a ruinous effect on the intelligibility of these lectures; and, if generally applied, it would have a ruinous effect on the intelligibility of science. This particular way of all flesh is a way along which we ought not to hasten any faster than we are driven. The data will outrun the models fast enough; at any moment of time we should enjoy the maximum of simplicity compatible with that moment.

In Table III, I list the isotopes of the first two elements, hydrogen (symbol H) and helium (symbol He). (There is an extra isotope of hydrogen among them—I omitted it from Table II because it is unstable, as we shall later see.) The masses quoted in the second column are not quite the same as those which are given in Table II. These in fact are the masses of the *nuclei;* the others were the masses of the *atoms,* that is, of the *nuclei plus the planetary electrons.* The mass of the electron is only 0.0005, so that the differences are hardly enough to notice; once in a while some physicist makes a misstep by failing to notice them, but usually we may disregard them.

Table III

${}_1H^1$	1.0076	Proton	⊕
${}_1H^2$	2.0142	Deuteron	⊕○
${}_1H^3$	3.0165	Triton	⊕○○
${}_2He^3$	3.0160		⊕⊕○
${}_2He^4$	4.0028	Alpha particle	⊕⊕ ○○

You notice also that the nuclei have *symbols,* given in the first column. To write the symbol for a nucleus you begin by writing the chemical symbol for its element, such as H for hydrogen and He for helium. Then southwest of it you write its "atomic number," which is its charge expressed in terms of the natural unit *e,* and is accordingly 1 for hydrogen and 2 for helium. Then northeast of it you write its "mass number," which is the integer nearest to the value of its mass. The table shows five symbols: ${}_1H^1$, ${}_1H^2$, ${}_1H^3$, ${}_2He^3$, and ${}_2He^4$. People sometimes leave out the atomic number, for the good and sufficient reason that it is excess baggage, adding no information to that already supplied by the chemical symbol. Thus, "uranium 235" is a full name for the sinister isotope which is the most notorious of all nuclei; and the full description of our unit of mass is that it is one-sixteenth of the mass of an atom of "oxygen 16." However, there are physicists and chemists who have not yet got around to doing their duty of memorizing the numbers of all the elements, and of course we do not expect such a feat of the laity; so in general it is a good idea to hitch the atomic number onto the chemical symbol.

At this point I remark that four of these five nuclei have *names.* This is not a general quality of nuclei, and happy we may be, since it would be appalling to confront an array of more than five hundred names. However, four of these first five *are* named, and there are three of the names which you must remember: *proton* for ${}_1H^1$, *deuteron* for ${}_1H^2$, and *alpha particle* for ${}_2He^4$. Proton and deuteron are the Greek words for first and second; here a knowledge of Greek is no disadvantage. You may even for good measure remember that *triton* means third and is the name of $_1H^3$, but this nucleus and its name are both rare. The others are abundant and important.

Finally, looking at the last column, you notice that the nuclei have *pictures*. These are composed of circles, some of them having crosses inside them while the rest are vacant. These are meant to imply the cross sections of spheres. At this point we take our first step into the theory of the structure of nuclei, commonly known as "nuclear theory."

We begin by supposing the proton to be an *elementary particle,* structureless, utterly simple. You may regard it as a hard round little marble, only 10^{-13} of a centimeter in diameter; it would take about twenty-five millions of millions of them laid side by side to span a linear inch. I presume that there may be some mathematical physicists in this audience, and I can almost hear them gnashing their teeth as they hear me propose a model so solid, so concrete, so earthy. They would probably like me to speak of potential curves and draw them on the blackboard; and they can properly claim that with their picture of a proton they could lead you farther than I can with mine. However, their picture is sufficiently close to mine to justify me in using mine for the purposes of these lectures; and you and I will play marbles among ourselves while the mathematicians puzzle out the details of their much more sophisticated image. I ask you further to imagine that on the side of each little round proton is painted a little cross or plus sign. This is to remind you of its positive charge of one unit. The circles with the enclosed plus signs in my present and future figures stand for cross sections of protons.

We now turn to the deuteron, which has about double the mass of the proton, but just the same charge. Were it not for this equality of charge, we might play with the notion of modeling the deuteron as a pair of protons stuck together. However, such an arrangement would have a double charge; the notion is stillborn. If we are to have a model of the deuteron comprising one proton and one other elementary particle, this other must be of about the same mass as the proton but must not have any charge at all. We postulate such a particle, and we call it "neutron" by reference to the fact that it is electrically neutral. It too shall be regarded as a little round marble of about the same size as the proton; but we will not paint any plus sign on its imaginary side. The empty circles of the diagrams in Table III stand for cross sections of neutrons.

You may feel that so far we have made no progress, since we have taken care of two nuclei only and we have introduced two elementary particles for the purpose. This would be an absolutely just criticism. If we went on like this, bringing in a new elementary particle for every new nucleus, we should indeed be wasting our time, and we could find pleasanter ways of wasting it. But the opposite is true. There are hundreds of nuclei still to come, but for each and every one of them it is found sufficient to postulate protons and neutrons and nothing else. The nucleus ${}_1H^3$ is one proton and two neutrons. The nucleus ${}_2He^3$ is two protons and one neutron. The nucleus ${}_2He^4$ is two protons and two neutrons. The nucleus ${}_8O^{16}$, our standard of mass, is eight protons and eight neutrons. The nucleus ${}_{92}U^{235}$, the terrible isotope of uranium, is 92 protons and 143 neutrons. So it goes throughout. We build all our nuclear structures out of only two kinds of marbles, and they serve our purposes. This is the "proton-neutron model" of the nuclei. Over and above all this, we have discovered the "free" neutron, the neutron dissevered from protons, fluttering around in space by itself on a temporary vacation from its agelong task of being a part of one nucleus or another.

Later on I shall be narrating the story of the free neutron and how it is set free. Right now I take the chance of pointing out the strong conservatism of the physicist. Since the discovery of isotopes and the measurements of nuclear masses a quarter of a century ago, there has never been a moment when this proton-neutron model of the nucleus would not have been the simplest and the best. Yet it was proposed only seldom, and it never made headway; or, speaking more colloquially, it never caught on and it never took—until the free neutron was discovered. People preferred to regard the deuteron (for example) as a pair of protons with a negative electron hanging onto them to cancel half their charge. That was a model of three particles instead of two, but the three particles were of two familiar kinds, and that made all the difference. If they had known about uranium 235, they would have built their model for its nucleus out of 378 particles altogether—235 protons and 143 electrons—instead of using 143 neutrons and 92 protons. So great was their reluctance to buy a simpler model at the price of an unknown particle! When the free neutron was found, their reluctance vanished at once, and the electrons were promptly erased from the nuclear picture. But I do not guarantee that they will never be restored!

Proton	⊕	**Charge 1**	**Mass 1.0076**
Neutron	○	**Charge 0**	**Mass 1.0089**
Negative electron	●	**Charge −1**	**Mass 0.0005**

FIGURE 1

The upper part of Figure 1 presents the two fundamental particles with which we build our models of the nuclei. You see that the mass of the neutron is not given as exactly as that of the proton; the neutron is very slightly the heavier of the two. The word "nucleon" is coming into use to subsume the neutron and the proton. The lower part of the figure presents the negative electron. These are our three fundamental material particles, three of the gods of our pantheon. They are not the whole of the pantheon, for there are other material particles of transient existence, and there is also the world of light which interpenetrates the world of matter. These three, however, are the building bricks of all our material atoms.

These particles have other properties than merely mass and charge. For instance, they rotate, like the earth rotating on its axis; and, another point of resemblance with the earth, they are magnets. These are very important properties, but to avoid exceeding my time I must dismiss them with this single mention. However, there is one more property of the proton and the neutron which is not merely important, but vital to their services. They are able to stick together or, in perhaps more elegant language, to *cohere.* Were it not for this property our models would be no models at all, no more than a heap of sand or a cloud of dust could be a model for a house. Now we must examine more closely this concept to which I have given the colloquial name of "sticking together" and the more learned name of "cohesion."

My colloquial term may suggest that there is something like mortar or glue covering the surfaces of all protons and neutrons. This, however, is not a necessary idea. This table before me is surely not cemented to the floor, and yet I should not care to lift it. It is held to the floor and the earth not by glue, but by a force which we call *gravity.* This will provide us with a safer analogy. But instead of speaking of *force,* let me speak for a while of *work.*

Work is something which has no natural unit and many conventional units. One of the conventional units of work has a self-explanatory name: it is the "foot-pound." If this table weighs 50 pounds and I lift it through 1 foot, I shall do 50 foot-pounds of work upon it. It will take 100 foot-pounds of work to lift the 50-pound table 2 feet, and 1000 to lift it 20 feet. How much work would it take to lift the 50-pound table from here to infinity, out beyond the depths of interstellar space?

It may seem that in order to separate earth and table by an infinite distance, we should have to do infinite work. However, this is not so, because the force of gravity diminishes as earth and table recede from one another, varying according to Newton's law of the inverse square. By use of the integral calculus we can calculate just the amount of work required to divorce utterly and completely the earth-and-table pair. This amount is roughly one billion foot-pounds.

Now let us go back to the deuteron.

It takes a definite amount of work to pull the proton and the neutron apart, divorce them from each other, and convert them into bachelor particles roaming freely around the world. This work has been measured, and its value is accurately known. The foot-pound, as you readily guess, would be a very unsuitable unit for expressing it, just as the ounce and the gram were unsuitable units for nuclear masses. The physicists have a special unit for the purpose; but we have had enough of units for today, and I will defer this to my second lecture. Meanwhile let us get rid of this word "work" with its unpleasant connotations. I told you that we would play with marbles; it is perhaps unfair to involve you in the work of pulling the marbles apart. For the plebeian word "work" I will substitute the aristocratic word "energy." To pull the deuteron apart we have to give it a certain measurable amount of energy. This is just a new way of saying the same thing, but somehow it sounds more noble.

Of course, it is not only the nobility of the word which induces the substitution, but primarily the fact that *energy* is a grand general concept of which this is but one of the aspects. I shall not be giving you any general definition of energy, because it is one of the concepts which has to mature in the mind through long experience. There are many forms of energy, and they require special names. This I might call "energy of divorce," but I will approach the usage of the physicists by calling it "unbinding energy." It takes a billion foot-pounds to unbind the 50-pound table from the earth, and it takes 2.18 very much smaller units of a special and suitable kind to unbind the proton from the neutron. The physicists prefer to call it "binding energy," since it is also the amount of energy which would be released if a free proton and a free neutron were to meet one another in the depths of space and decide to pair up as a deuteron. I could also speak of the binding energy of the earth-and-table system, though we could not avail ourselves of this unless some kindly supernatural being were to take the table out to the depths of space and let it fall back to earth again. Even this favor would do us no good, unless we were to climb above the atmosphere to meet the table, for otherwise the poor table would be all burned up by friction as it slid through the air. In the subatomic world there is no friction, and we can recover the binding energy when particles formerly free decide to bind themselves together.

Here now is my final illustration of this lecture, Figure 2. It presents to you again the proton, the neutron, and the deuteron; their names, their symbols, and their masses. Lastly, here is a sum in simple addition. It transpires that the masses of the proton and the neutron add up to 2.0165, whereas the mass of the deuteron is 2.0142.

Proton	⊕	Mass	1.0076
Neutron	○	Mass	1.0089
		Sum	2.0165
Deuteron	⊕○	Mass	2.0142

FIGURE 2

Here *is* a pretty pickle. I had told you that the deuteron consists of a proton and a neutron, but now it turns out to be lighter in weight than those two. How very odd, that after so long a preparation I should suddenly devastate my own argument by uncovering a flaw like this! But it isn't a flaw, and instead of devastating my argument it has made sound the argument which otherwise would be untenable. This paradox we will explore in the second of these lectures.

2.

I VENTURE to suggest that twenty-three hours ago I left you with a chaotic mental image of a cloud, or dust storm, or sand storm, or whirlwind of particles electrified and non-electrified, protons and neutrons and electrons racing madly around in space and giving, in some mysterious way, a very *un*reasonable facsimile of the world in which we live. I should not be too dissatisfied if I did create such an impression, even though I did mention some features of form and order, and hope to impress you more strongly with these as we proceed in these lectures. Perhaps that chaotic image of racing and whirling and dancing protons and neutrons and electrons does correspond to the world as it was, millions of millions of years ago. Nobody will ever be able to prove such a statement or to disprove it; but sometimes it is of use to make an unprovable and undisprovable statement. If that was the state of affairs in "the dark backward and abysm of time," we must also imagine that in the subsequent ages the protons and the neutrons have been gradually clustering themselves together into those hard, compact, tight-packed little clumps that we call "nuclei." We now live in a world in which most of the protons and nearly all of the neutrons are clustered, and with the aid of the electrons these clusters form the atoms which account for the wonderful diversity of this world of ours.

Yesterday I presented a dozen or so of these clusters to you, but as my lecture went on I gradually contracted our field of view until at the end we were looking at just one of the clumps: the simplest cluster of all, the simplest of the composite nuclei, the neutron-proton pair which constitutes the *deuteron.* Look again at Figure 2, and notice anew the neutron, the proton, the deuteron, their masses, the binding energy of the deuteron—and notice the awkward discrepancy which emerges from the arithmetic. The sum of the respective weights of the neutron and the proton is 2.0165; in combination they weigh 2.0142.

There is no error here, and this is not a situation that can be resolved by forcing the figures a little up or a little down, in the hope that future measurements will justify us in choosing values which make the arithmetic fit. Moreover, this is nothing peculiar to the deuteron. *All* the composite nuclei have this same anomaly. Every composite nucleus that we have ever measured has turned out to be lighter than the sum of the masses of the particles that go into it. This means that I shouldn't have called it an anomaly; it isn't an anomaly, it is a rule. It is as if, whenever you went to the grocery and picked out oranges and grapefruits one by one and had the grocer put them in a bag, the contents of the bag ever and always weighed less than the grapefruits and the oranges had weighed when you lifted them out of the showcase with your hands. Such a rule would attract attention, to say the least. On one level of sophistication, you would be rude to the grocer; on another, you would suspect some curious aberration in the scales; on a third, you would begin to conjecture that the act of putting them into the bag did something to the oranges and the grapefruits. Of these three choices, neither the first nor the second is of any use when dealing with protons and neutrons; but the third hits somewhere near the point.

The point may be paraphrased as follows.

When the proton and the neutron are paired together as a deuteron, there is something which differentiates them from the free proton and the free neutron. On one level of speech, they are sticking together. On a higher level of speech, they are cohering. To say the same thing on a still higher level of speech: it takes energy to pull them apart. Now, *energy has mass.* When you have pulled these nucleons apart—or when some agent has pulled them apart—they have received energy from you or from the agent, and also *they have received the mass of that energy.*

Now reverse the process, in imagination. Conceive a free proton and a free neutron wandering around in space. They approach one another, they attract one another, they collide, and they cohere. In cohering they lose their binding energy, and with it they lose the mass of the binding energy. They weigh less than they did before, because some of their weight departed when the binding energy was lost. The discrepancy in the arithmetic is not fallacious; it is a true deficit in mass which is disclosed. *The deficit of mass is the mass of the binding energy.* Like the binding energy in the nuclei, the discrepancy binds the theory together and makes it a coherent whole.

Figure 3 exhibits the symbols, the models, the masses and the mass deficits of the six simplest nuclei. The first two of these are the fundamental marbles, the bare neutron and the bare proton; their mass deficits, of course, are zero. In the fourth column and the fifth, the other mass deficits are expressed in two units. The fourth column, under the superscription Q (M.U.), exhibits the mass deficits in terms of the mass unit with which we are now acquainted. The fifth column, under the superscription Q (Mev), exhibits the binding energies in terms of the unit which I am now on the verge of defining. The last column shows the quotient when the binding energy is divided by the number of particles in the nucleus.

			$Q_{M.U.}$	Q_{Mev}	Q/N
${}_0n^1$	○	1.0089	0	0	0
${}_1H^1$	⊕	1.0076	0	0	0
${}_1H^2$	⊕○	2.0142	0.0023	2.18	1.09
${}_1H^3$	⊕○○	3.0165	0.0089	8.3	2.8
${}_2He^3$	⊕⊕○	3.0160	0.0079	7.4	2.5
${}_2He^4$	⊕⊕ ○○	4.0028	0.0302	28.1	7.0

FIGURE 3

For remembering the principle it might be helpful to the listener to try reversing a couple of well-known verbs. We speak of people *massing* themselves together in a crowd, but when it comes to nucleons, it would be better to speak of the protons and the neutrons *de-massing* themselves together in a cluster. We speak of a person amassing a horde; but when it is a question of transmutation, it would be better to speak of a physicist *de-massing* the nucleons by bringing them properly together. The principle is confirmed by experiments on transmutation, hundreds on hundreds of them, from among which I will select a couple of illustrations in due time. However, it was announced by Einstein,* no fewer than forty-two years ago—before there was any transmutation worked by man, before there was any nuclear physics, before anyone even knew that there are nuclei in atoms. I hope to be forgiven for not expounding Einstein's argument. It is difficult, and it is deep and is derived from the highly mathematical theory of relativity. It was, in fact, just what too many people like to call an "ivory-tower" speculation; but out of that ivory tower there emerged the antecedents of atomic energy and the atomic bomb.

This has a lesson for us. Now and then you read in the papers that someone or other has said that we ought to keep secret every scrap of scientific knowledge connected in any way with atomic energy, lest we put some foreign power in a position to do us harm. Now, this is an impossible proposition. Einstein's paper of 1905 was published in a German journal. Try to imagine Kaiser William II, or his Prime Minister, or his Minister of War, or his Chief of the Great General Staff—try to imagine any of these gentlemen reading Einstein's manuscript and divining that, if they let it go to press, they would start a train of events which in forty years would enable the United States of America to overthrow Germany's last ally. You may suggest that these political and military leaders would have been well advised to delegate some scientist to read the manuscript and do the divination. But Einstein himself did not foresee the consequence in question; how then should anyone else have foreseen it?

Einstein's argument culminated in the equation now world-famous

$$E = mc^2$$

Here E stands for energy, m for the mass associated with that energy and c for the velocity of light. If you ask how the velocity of light gets into this galley, I can only advise you to

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* There had been partial anticipations, forming a story fascinating but too difficult for these pages.

set aside a year or so for the study of electromagnetism and of relativity. Better just take the presence of c as a sign of the intimate implication of light with electricity and matter, and regard this equation as a formula for giving the mass of any particular amount of energy. But to make practical use of this formula, we must decide on our units. The unit of mass will not trouble us further; it shall remain one-sixteenth of the mass of an atom of oxygen 16. The unit of energy will require some thought. Let us rush courageously upon this nettle and grasp it firmly.

I have already introduced to you one unit of energy—much too large to be suitable—which is called the foot-pound. This was defined as the work which must be done to lift a pound weight through 1 foot. If, after lifting the pound weight through the foot you drop it, then, when it falls back to its original position, it will be moving with a certain speed—about 8 feet per second. It therefore has a certain energy of motion, *kinetic energy,* we call it. This kinetic energy is the same as the work which you put into the pound weight to lift it; it is the foot-pound of our definition.

The unit which I next introduce is called the "electron volt." The name may suggest that instead of dropping a pound weight, we are going to drop an electron. This idea is correct as far as it goes, but it does not go far enough; there is a further important distinction. The falling pound weight gets its speed from the force of gravity, but the electron is to get its speed from an *electric* force. To set the stage for such an operation, let us imagine an x-ray tube such as you see in your dentist's or your doctor's office.

Inside the x-ray tube there is a filament which is kept incandescent, like the glowing filaments in your radio tubes. Electrons are perpetually boiling out of this hot filament. Elsewhere in the tube there is a metal target positively charged, which by virtue of its charge draws the electrons to itself. We will suppose that the voltage between the target and the filament amounts to just 1 volt, though an actual x-ray tube requires many thousands of volts. The electrons arrive at the target with a speed derived from the electric force and not from gravity. (Gravity does indeed make a contribution, but it is a negligibly small one.) Owing to this motion the electron has kinetic energy. The amount of this kinetic energy is *1 electron volt.* This is our definition. If in the tube the voltage were, say, thirty thousand, the kinetic energy of each electron arriving at the target would be thirty thousand electron volts.

This unit is remarkably well suited to atomic phenomena —and here I do *not* mean nuclear phenomena, I mean *atomic* phenomena in the proper sense. Here are some illustrations. You all remember having heard that heat is molecular motion. The atoms of the air of this room, for instance, are flying about with speeds averaging about half a mile per second, and that is the source both of the pressure of the air and of the warmth of the room. Their average kinetic energy is about one twenty-fifth of 1 electron volt. In the flame of the electric arc, the hottest region at our command, the average kinetic energy of the atoms approaches but does not quite reach 1 electron volt. Visible light, from the red to the violet end of the spectrum, is formed of corpuscles having energies from 2 to 4 electron volts. The energy required to unbind the electron from a hydrogen atom is 13.6 electron volts. Now some chemical illustrations. When you burn coal, the heat comes ultimately from the combination of carbon atoms with oxygen atoms. The release of energy into the form of heat amounts to about 1.5 electron volts per pair of combining atoms. If you set gasoline afire or detonate a charge of TNT, the result is considerably more impressive and may lead to the suspicion that the release of energy is considerably vaster. Not at all: the major difference between TNT and coal is that the former burns faster. If you penetrate to the elementary process which underlies even the most violent of chemical explosions, you find that the release of energy amounts to 2 or 3 electron volts when the individual molecules make their individual contributions. The electron volt is thus a very handy unit for chemical and other truly atomic phenomena, and one wonders how we ever managed so long as we did without it.

In dealing with the nuclear phenomena—and these, I remind you again and again, are the topic of these lectures—the electron volt proves much too small a unit. To express nuclear energy releases in electron volts is somewhat like weighing coal in ounces, only more so. We use as our unit the *million* of electron volts, denoted by Mev. You notice that I have implied that nuclear energy releases are millions of times as great as chemical energy releases. This is going to be confirmed by detailed examples: but let us finish with our present enterprise, which is to convert Einstein's formula $E = mc^2$ into something of practical use for translating mass into energy and energy into mass.

The rule is: *to one mass unit correspond 931 millions of electron volts:*

$$\text{One mass unit} = 931 \text{ Mev}$$

Thus, the mass of the proton corresponds to 938 Mev, the mass of the electron to 0.511 Mev or 511 thousands of electron volts.

Now look again at Figure 3 (page 27) and the information about the six lightest and simplest nuclei—the two elementary particles and the four simplest of the composite nuclei. Next to their symbols and their masses, you see the values of their mass deficits expressed in mass units and the values of their binding energies (which are the same things, differently named) expressed in millions of electron volts. In the last column you see the quotients formed by dividing the mass deficit of each composite nucleus by the number of particles which have clustered together to form that nucleus. This is the average loss of mass experienced by the individual particle of the cluster. You note that this quotient increases as the number of particles increases. This means that the more numerous the particles of the cluster, the greater the attraction which each one of them experiences, and the greater therefore the loss of mass which each one of them experiences. Now it is time for me to say something about the nuclear forces which are responsible for this effect..

You may have noticed yesterday that, when speaking of the attraction between earth and table, I began by speaking of the force of gravity to which the attraction is due, and I left the binding energy to the end; and then when I went over to the case of the deuteron, I spoke at once of the binding energy and said nothing about the force. This was because, in the case of the deuteron, we know the binding energy directly, whereas we know less about the force than we do about gravity. However, we do know some things about this mighty nuclear force of attraction, and it is essential to have some of these in mind.

To begin with negative statements: this mighty nuclear attraction is *not* gravity, and it is *not* an electrical force. I shall probably not mention gravity again in these lectures, because by comparison both with nuclear forces and with electrical forces it is generally so weak that it is insignificant, and we can afford to forget about it. As between the nuclear attraction and the electrical forces, the situation is rather more complex. In the *immediate neighborhood* of a proton or a neutron, the nuclear attraction is far, far more potent than any electrical force which may exist in the same region. You can deduce this from the models of the nuclei symbolized by ${}_2He^3$ and ${}_2He^4$. In each of these nuclei there are two protons, and they repel one another by an electrical force which is the well-known electric repulsion between two charges of identical sign. Nevertheless these nuclei cohere, and they cohere very strongly, as their mass deficits show. The nuclear attraction is therefore strong enough to triumph over the electric repulsion and to triumph by a big margin.

This, however, does not mean that the electric force is something we can safely forget about, as we forget about gravity in nuclear physics. Quite the contrary! When two protons are far enough apart, the nuclear attraction is much *weaker* than the electric repulsion. Do not infer that by "far enough apart" I mean a couple of miles or anything like that. When two protons are 10^{-12} centimeter apart—say one millionth of one millionth of one inch—the electric repulsion is stronger than the nuclear attraction, and the protons tend to depart from each other. We express this fact by saying that the electric repulsion is a "long-range force" and the nuclear attraction is a "short-range force." The electric repulsion starts with a relatively low value at a distance of, say, 10^{-13} centimeter, and falls off with increasing distance according to Newton's law of the inverse square, which is a relatively gentle decline. The nuclear attraction starts with a relatively high value at the small distance and tumbles precipitously down. The balance occurs somewhere under 10^{-12} centimeter, and at all greater distances the electric repulsion is the stronger of the two forces.

You may recall that yesterday I spoke fleetingly of the possibility that the feet of the table might be glued to the floor, only to discard it right away. Here is another point where the analogy of glue can be of some help. If the feet of the table were glued to the floor, I should have to give the table a pretty vigorous wrench; and if I were strong enough the table would then quite suddenly be free, before it had even been displaced by more than a very small amount. The deuteron behaves like this: if its proton and its neutron are suddenly wrenched apart, they are free from one another before they have been separated by very much. The glue then serves as a passable analogy to the short-range force of nuclear attraction. In the case of the deuteron there is no analogue to the long-range force of gravity, because there is no electric repulsion between the proton and the neutron. But if we had two *protons* cohering together and the force of gravity were a *repulsive* force, a fuller analogy could be made. We should break the glue by wrenching the table away from the floor, and then the table would take its leave and fly off through the nearest open window to the depths of interstellar space.

Now we are on the threshold of one of the most important compartments of these lectures, the compartment devoted to the *transmutation of the elements*.

Here in Figure 4 are some of our now-familiar nuclei, both elementary and composite, with their now-familiar masses adjacent to their pictures. We have four elementary particles, two of each kind. They are exhibited in three arrangements or *groupings*. In Grouping I all four are free, and their total mass amounts to 4.0330. In Grouping II the four are paired into two deuterons, and their total mass has gone down to 4.0284. In Grouping III, two protons and one neutron are combined into a $_2He^3$ nucleus, and the remaining neutron is off by itself; the total mass is 4.0249. There is also a grouping IV, in which two neutrons and one proton are combined into a $_1H^3$ nucleus and the remaining proton is off by itself. Forget about it for the present: its turn will come.

	○	○	⊕	⊕	Mass
I.	1.0089	1.0089	1.0076	1.0076	4.0330
	⊕○		⊕○		
II.	2.0142		2.0142		4.0284
	⊕⊕○		○		
III.	3.0160		1.0089		4.0249

FIGURE 4

Now I aver that there is *a tendency in Nature for the nucleons to seek out and abide in the grouping of least energy and least mass.* Grouping III, in other words, is the most *stable* of these three; Groupings I and II are *unstable* and want to transform themselves into Grouping III. This is a principle, and one of the most important in nuclear physics, matched in importance only by the principle that nuclei consist of neutrons and protons and by the principle that deficit of mass is binding energy.

This principle raises an immediate question. If there is a tendency for Grouping II to go over into Grouping III, why are there any deuterons left? The world is full of deuterons, and presumably they have been bouncing around for ages and ages; why have not their constituent protons and neutrons already reassorted themselves, leaving nothing but $_2He^3$ nuclei and free neutrons to ramble around the world in place of the vanished deuterons?

The answer to this question is known: it comes in two stages. First, all the deuterons are nuclei of atoms. Some are nuclei of free atoms of heavy hydrogen; each of these has a planetary electron circulating around it at a distance of about 10^{-8} centimeter. The rest are nuclei of atoms which have gone into chemical combination with other atoms, and these usually have more than one planetary electron circulating around them at distances of 10^{-8} centimeter or thereabouts. When two such atoms bump into one another, they rebound from one another as if their electrons were solid elastic shells surrounding and protecting the nuclei. This is rather difficult to understand, but it is a fact. The deuterons are nicely shielded from each other, like medieval knights in a tournament with no joints or gaps in their armor. Their armor gets some heavy blows, but none which pierces to the heart.

How about ripping this armor off and exposing the deuteron? This is possible, but it is not sufficient. We *can* rip the electronic armor off by putting heavy hydrogen gas into a tube and sending an electric current through it. By doing this we remove the electrons from the atoms, and deuterons rush around in the discharge, unprotected and bare. Only, for our purpose, they are not unprotected, and they are not bare. They are still wearing the undetachable armor of their electric fields. Each of them has a positive charge, and each of them pushes the others away with this long-range force of electric repulsion. They cannot start upon the desired reassortment or rearrangement or regrouping of their elementary particles until they are close enough together so that the short-range nuclear attraction can set to work. But the short-range nuclear attraction cannot set to work until they are within 10^{-12} centimeter of one another, and they never come so close to one another because of the long-range electric repulsion.

This is where man comes into the picture.

Man has indeed solved the problem—or, to pay credit where it is due, the experimental physicists have solved the problem—of putting the deuterons so close together that the nuclear attractions come into play, and the four particles making up the two deuterons get a chance to regroup themselves into the grouping of lesser mass and lesser energy which consists of one free neutron and one nucleus of helium 3. You have already seen that this is the problem of overcoming the electric repulsion between the two deuterons. It is solved by projecting one deuteron against the other with tremendous speed and high kinetic energy, so that the projectile wins its way to the target against the repulsive force which strives to hold it back. This is achieved with the aid of a *high-voltage machine.*

In the quarter of a century since transmutation was begun, several metaphors and similes have come into frequent use. Some of them are good, and one is definitely bad. It is usually good to speak of projecting or firing one deuteron against another deuteron or, more generally, of firing a deuteron or a proton or an alpha particle against a nucleus of any other kind. This is a fairly apt description of what we do. It is passably good to speak of the flying deuteron piercing its way to the stationary deuteron against the obstacle of the repulsive force, more or less like the bullet piercing its way through the armor to the heart of the medieval knight who had the bad luck to defy a newfangled gun. But it is thoroughly bad to speak of the result as "atom smashing" as too many people do.

If the word "smashing" suggests anything, it suggests that the smashed object is converted into worthless fragments. But our little marbles are not injured in the least when we succeed in bringing one cluster of them into contact with another cluster of them. They merely take advantage of their momentary proximity to rearrange themselves in a manner corresponding more nearly to their desires, like people cutting in on one another at a dance. Our high-voltage machine enables us to bring the dissatisfied couples together; what happens thereafter is determined by their wishes, not by ours.

There are several kinds of high-voltage apparatus of which the most famous is the cyclotron. To explain the cyclotron it would, however, be necessary to speak in some detail of the motions of charged particles in magnetic fields and to introduce the vacuum-tube oscillator: and to avoid these complications I will take as my example the "electrostatic generator." There is justice in this policy as well as convenience, for the electrostatic generator, highly as physicists prize it,

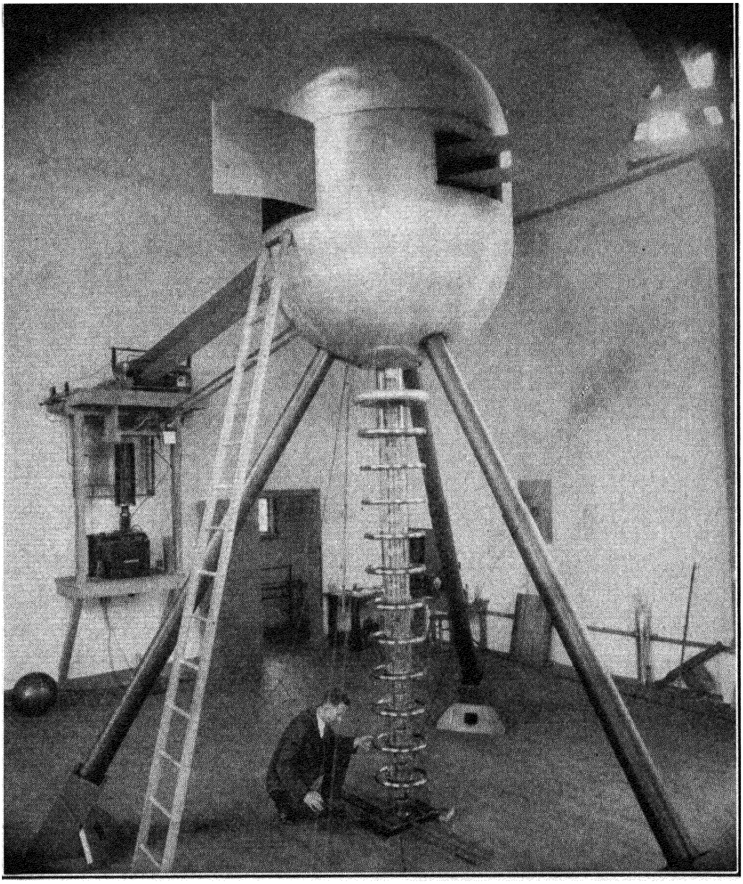


FIGURE 5

has been rather obscured in the public mind by the glory of its rival.

In Figure 5 appears a large hollow globe of metal, straddling on three supports, with three holes in its side through two of which a belt is seen to pass. The farther of these belts carries positive electric charge into the globe. The positive charge is loaded onto the belt over on the left of the picture; the belt carries it into the hollow of the globe, and there it leaks off onto the points of a comb, which is connected by a wire to the globe itself. The charge spreads itself over the surface of the globe, and the continuously running belt goes back and is loaded with more charge.

As this process goes on and on, the globe becomes more and more powerfully charged. One might expect the limit to be reached when the accumulated charge repels the oncoming charge so strongly that the motor can no longer force the belt to continue its rounds. This is not, however, what sets the limit. When the accumulated charge attains a certain magnitude, it bursts out of the globe through the air in a terrific spark, with an alarming resemblance to a bolt of lightning. The art of constructing a useful generator is largely the art of deferring the advent of this spark. For this purpose, in the instrument shown in Figure 5, the globe was made very large and smooth and was placed in a high-ceilinged room. Other such instruments have been mounted in the open air; still others have been immersed in oil or enclosed in tanks filled with gas at a high pressure. The pictured instrument, one of the earlier and less potent of its kind, was nevertheless able to hold a charge so great that the voltage between globe and floor surpassed a million; we will postulate for convenience one million volts.

The other belt operates a dynamo which applies a modest voltage across a tube which, we will suppose, contains the second isotope of hydrogen in gaseous form. This voltage provokes a discharge in the tube, and thereby some of the atoms are deprived of their planetary electrons and their nuclei are left to wander free. These nuclei are deuterons. They wander out of an orifice in the tube, into the (evacuated) glass column which is seen extending vertically downward from the bottom of the globe; and here they fall a prey to the electric repulsion which exists between their positive charges and the mighty positive charge assembled on the globe. Through the evacuated column they are driven; faster and faster they go as they approach the floor. When they are at the level of the earth they have "fallen through one million volts," as physicists say. What then is their kinetic energy? Why, *one million electron volts!* And now we become aware of another advantage of our chosen unit of energy—the voltage of the accelerating machine gives us the energy of the bombarding particles, without any fiddling-about with conversion factors.

The deuterons with their energy of 1 Mev now pass through the level of the floor; and next, in a subterranean observing room, they meet the end of the tube, which is covered over with a plate or film of some chemical compound rich in the second isotope of hydrogen, rich therefore in atoms containing deuterons. It is not necessary to strip these "target" deuterons of their armor of planetary electrons; the million-volt bombarding deuterons pierce easily through the armor, and some of them—percentagewise a very very few—come so close to target deuterons that the nuclear attractions come into play, the fundamental marbles regroup themselves in the grouping of lesser energy and lesser mass, and the newborn nuclei dash away with the kinetic energy born from the diminished rest mass.

In Figure 6 we see the tracks of two such newborn nuclei, springing in opposite directions from the scene of a transmutation which occurred within the target plate. It seems strange that the tracks of such tiny objects can be visible and, indeed, conspicuous; and it *is* strange, but true. The tracks, however, do not appear unless the stage is properly set for them. To begin with, the nuclei must run through air (or some other gas). They pierce through many atoms of the air; and by their electric attraction for the planetary electrons of these atoms, they pull some of these electrons loose. For a small fraction of a second, the path which the nucleus followed is bestrewn with these loose electrons and the atoms from which they were torn—"positive ions" these last are called.

The presence of these loose electrons and these positive ions does not of itself make the path a visible trail. One more condition must be fulfilled: the air must be *supersaturated* with water vapor. Given this condition, the vapor settles down upon the electrons and the ions and invests each one of them with a visible droplet of water. Now the path *is* visible, and indeed conspicuous, as the picture and others like it (Figures 7, 10, 11) show us. Like a meteor plunging into the high atmosphere, the departed nucleus has left behind it a lingering trail; but it is a trail of fire which the meteor leaves, and this is a trail of water.

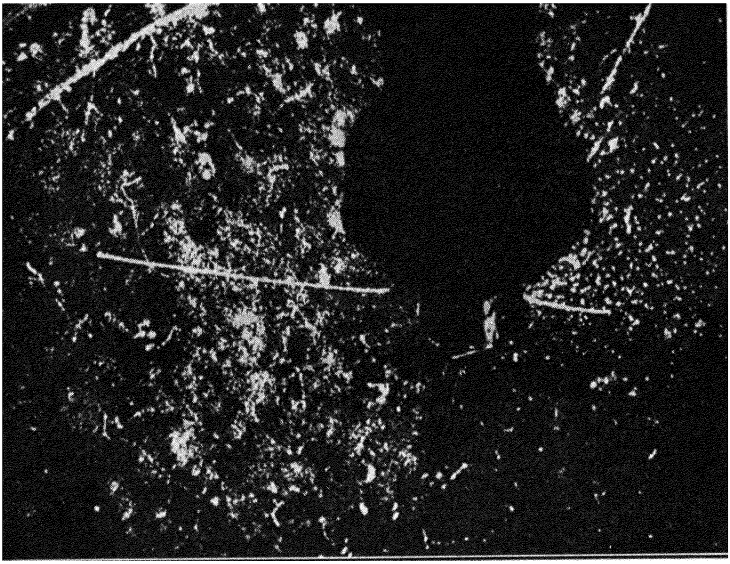


FIGURE 6

There is, of course, an art in producing these trails. Air does not remain supersaturated; it has to be put into that condition a fraction of a second before the nuclei start on their voyages. This is done by cooling the moist air suddenly and sharply. The moisture-laden air is confined in a glass-walled box or chamber surrounding the end of the tube where the target lies awaiting the onrushing deuterons from the high-voltage machine. One wall of the box is suddenly pulled out, and the air cools itself by expansion; this is the inverse of the familiar heating by compression which takes place when air is pumped into a tire. The nuclei which emerge just after such an expansion are those of which the trails are incarnated in water droplets and perpetuated in their images on a photographic plate. The chamber is called a "cloud chamber" and has given its name to the art.

I must now admit to having allowed, by omission, a misunderstanding of Figure 6. It has in fact been implied that the two tracks are those of a ${}_2He^3$ nucleus and a neutron, resulting from the reaction already described:

$${}_1H^2 \text{ and } {}_1H^2 \text{ into } {}_2He^3 \text{ and } {}_0n^1$$

This, however, cannot be, for a neutron cannot make a trail. Lacking electric charge, a neutron cannot detach electrons from atoms; no loose electrons and no positive ions are strewn along its path, no droplets appear to mark out its trail when the moisture-laden air is suddenly cooled. The tracks exhibited in Figure 6 are, both of them, the tracks of *charged* nuclei.

Well, the reason is that there exists a fourth possible grouping of two neutrons and two protons, which I omitted from Figure 4 in order not to introduce too many new facts at once. This is a grouping in which two neutrons and one proton cohere in a nucleus ${}_1H^3$, and the other proton is loose. In this grouping the total mass is 4.0241, which is less by 0.0043 mass unit than that of the grouping which consists of two deuterons. We infer that when two deuterons are brought close enough to one another there is a tendency for the following process to occur:

$${}_1H^2 \text{ and } {}_1H^2 \text{ into } {}_1H^3 \text{ and } {}_1H^1$$

The picture which is our Figure 6, and similar pictures, and evidence obtained in other ways all prove that this tendency is able to effectuate itself, and this process does occur. The fact that one of the trails is shorter than the other is no trick of the photograph. Both newborn nuclei come eventually to a stop, because they waste their kinetic energy in detaching electrons from the atoms of the air. The ${}_1H^3$ nucleus is the more massive and accordingly the slower-moving of the two, and therefore it comes earlier to a stop and has the shorter trail.

No one is wise enough to say why, when two deuterons are brought close together, it is sometimes the one of these two processes which happens and sometimes the other. However, there is an easier question which may occur to the reader. Why, in obtaining such a picture as that in Figure 6, do we not see tracks of nuclei originating some from one, some from

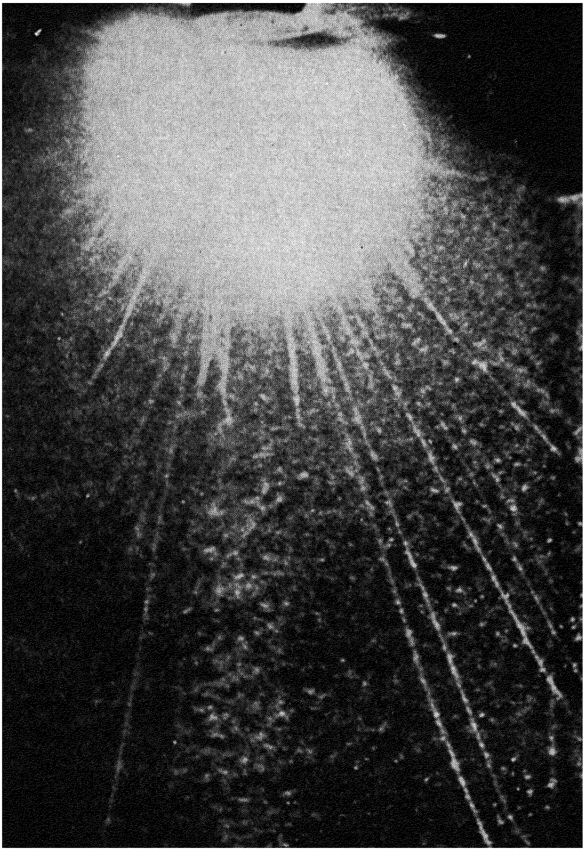


FIGURE 7

the other, of the processes? In answering this question, I shall be able to terminate this lecture with a very beautiful picture, which is Figure 7.

In the case of the second or proton-releasing process, the $_1H^3$ nucleus and the proton divide between themselves a kinetic energy amounting to 4.0 Mev. In the case of the first or neutron-releasing process, the mass available for conversion into kinetic energy is smaller, and the $_2He^3$ nucleus and the neutron have only 3.3 Mev to share. The charged nuclei have to traverse the wall of the tube which contains the target before they can enter the air of the cloud chamber and produce their visible trails. In passing through this solid wall they waste kinetic energy by detaching electrons from atoms, just as later they do in the air. The newborn nuclei resulting from the second process have kinetic energy enough and to spare; but the $_2He^3$ nuclei resulting from the first process are less richly endowed, and they are stopped in the tube wall.

To circumvent this obstacle, the cloud chamber is filled not with moist air but with the second isotope of hydrogen in gaseous form, and the deuterons from the high-voltage machine are projected through the thinnest possible wall right into the cloud chamber itself. In Figure 7, the aureole at the top is the region of the chamber which the bombarding deuterons perfuse: there are no distinguishable trails, for the trails are so many that they have coalesced into a single cloud. In the region of this cloud, both processes occur. The long tracks which traverse the whole of the picture are the trails of the newborn nuclei which spring from the latter process. The shorter trails which also emerge from the aureole and end in the middle of the picture are the trails of the $_2He^3$ nuclei resulting from the former process. Neutrons also were traversing the chamber when this photograph was taken; but, like an insidious poison detectable only through the harm it eventually works, they slithered through the gas silently and invisibly, leaving no trace at all.

3.

MY SECOND lecture culminated in our first example of the *transmutation of the elements.* It started with two deuterons, two pairs of our elementary particles or fundamental marbles, each of them composed of a neutron and a proton cohering strongly together. They were repelling each other by their long-range force of electric repulsion, so that it was needful to use a high-voltage machine to bring them together, one flying against the other. Once they were brought together their four elementary particles fell under the sway of the powerful short-range attraction and made use of it for attaining their hearts' desire. Their hearts' desire was to reduce their weight —this may be considered to impart a human element—and they achieved it by reclustering themselves so that both of the protons and one of the neutrons cohered together into a single cluster of three, while the other neutron was left by itself. Out of the two "old" nuclei there came two newborn nuclei, and the sum of the newborn masses amounted to less than the sum of the old masses. But the discarded mass did not just vanish; it remained on the scene under a new aspect as the kinetic energy of the newborn nuclei. Or, more precisely, it did not remain on the scene, for because they possessed it the two newborn nuclei raced swiftly away from each other.

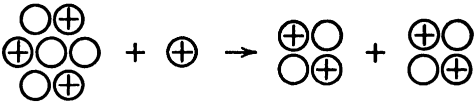
Such a process is called a *transmutation,* because there is hydrogen at the start and there is helium at the finish, and these are two different elements. The deuterons, I remind you, are nuclei of *hydrogen;* the newborn three-particle clusters are nuclei of *helium.* These invest themselves in due time with planetary electrons, and then we have helium gas. Whenever we make this process occur we make helium out of hydrogen, and we get a free neutron as a by-product. Some of the deeds this free neutron can do will appear later on in the story, and we shall see that it can do plenty.

I repeat that it is not proper to denote this process by the name of atom smashing, for nothing is smashed. Admittedly the impact of a fast-flying deuteron upon a stationary deuteron suggests a hammer blow, and admittedly when you hit something hard with a hammer you may expect to smash it; but the analogy is deceiving. Admittedly also, when you hit something hard with a hammer you are likely to think that the outcome is due entirely to the energy of your muscles, but this is not necessarily the case; it would definitely not be the case if the inquest should reveal that what you hit was a piece of dynamite. When you hit a stationary deuteron with a fast-flying deuteron you are really just putting the two together so that Nature can take its course. I do not say that the kinetic energy of the flying deuteron is lost. It reappears as part of the kinetic energy of the newborn nuclei, but usually it is only a small part, and the bulk of the energy of the newborn nuclei comes from the masses of the old ones.

I am sorry to be hammering away at this point with even more than the pertinacity of a high-voltage machine, but it is the most important point in all the field of transmutation and nuclear energy, and the physicists themselves were slow to grasp it in the early days of the art. Allow me to belabor it once more. I have said that the kinetic energy of the newborn nuclei amounts to the lost mass plus the kinetic energy of the original flying deuteron. In making this statement I was converting the lost mass into energy units by using Einstein's formula, which says that 931 Mev correspond to one mass unit. Now, it is a fact of the first importance that *the experiments have confirmed the formula.* We have measured the kinetic energies, and we have measured the loss of mass, and they agree. Indeed, we have made so many such measurements on so many different processes of transmutation that, if Einstein had not provided us with the formula in advance, we should ere now have been able to infer it from the data.

Now it is fitting to generalize by giving you other instances of transmutation. Here I suffer from an embarrassment of riches, for man has produced transmutations of types numbered not by the hundreds, but actually by the thousands. I cannot even choose the high spots, because there are so many high spots that the scene resembles the Himalayas much more than it can be likened to a mountain surrounded by foothills. History will guide me in my choices.

Here, for instance, is the first transmutation effected with *protons*. Protons were projected by a high-voltage machine against lithium, which, as we have seen already, is an element with two isotopes, lithium 6 and lithium 7. The nucleus of lithium 7 is an aggregation of four neutrons and three protons. Figure 8 exhibits, in symbols and in pictures, what may happen when a fast-flying proton succeeds in piercing the barrier of electric force surrounding this sevenfold aggregation. There are eight elementary particles now, and for an inappreciable moment they are all scrambled up together; then they depart in a pair of nicely assembled identical clusters of four. We recognize * these clusters; they are none other than the alpha particles presented in Lecture 1. Alpha particles are nuclei of helium, and accordingly lithium and hydrogen have been converted into helium.



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

0.0177 mass unit into 16.48 Mev

FIGURE 8

At the bottom of Figure 8 is shown the conversion of rest mass into kinetic energy which occurs in this reaction. You note that now I say "*rest* mass" instead of merely "mass." This change is made in deference to the theoretical physicists, who draw a careful distinction. When a particle is standing still, it has its *rest* weight or *rest* mass; when it is moving, it has kinetic energy and therefore it has in addition the mass of that kinetic energy, which enters as a sort of supplement to the rest mass. All the numerical values of mass which I have given in these lectures, and all which I have yet to give, are

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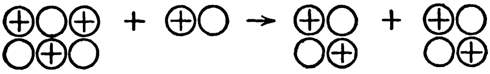
* Do not be distracted by the fact that in one figure the protons appear at opposite corners of the nucleus, in the others along one side. We do not know how the four nucleons are arranged; either picture is as good as the other.

values of *rest* mass. Now that this is said, I point out that this is a reaction which yields kinetic energy about five times as great as the process which occurs when two deuterons come together.

In Figure 9 appears a reaction of transmutation which comes to the same finish from a differing point of departure. Lithium is bombarded with fast-flying deuterons, and every now and then a deuteron wins its way to one of the sixfold aggregations of three protons and an equal number of neutrons, which constitute the nuclei of lithium *six*. Here is again the raw material for a pair of alpha particles. The values of rest mass inform us that if the eight elementary particles should see fit to reassort themselves into a pair of alphas, the rather spectacular weight of 0.0238 mass unit would stand ready for conversion into 22.15 Mev of kinetic energy. They do see fit, and the alpha particles spring forth in pairs with their tremendous energies for all to see and measure, as evinced by Figure 10. For several years this process was the extreme one, providing a greater supply of kinetic energy out of rest mass than any other which was known; now even it has slipped into the background.



$$_3Li^6 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4$$

0.0238 mass unit into 22.15 Mev

FIGURE 9

You were introduced to the alpha particles in their role as nuclei of helium atoms, and you have just encountered them as products of transmutation. Now you are to meet them as *agents* of transmutation. This is their supreme historic role; for under human control they were the first to succeed where every available weaker agency had been tried out and had failed. Here I show one of the first group of transmutations ever to be reported:

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

I give the formula and I do not draw a picture, for the nitrogen nucleus in question has fourteen nucleons and the oxygen nucleus has seventeen, and a clump of fourteen circles or of seventeen is too large to be held as a unit in the eye or the mind. This is a reaction starting with *helium* and *nitrogen,* ending with *oxygen* and *hydrogen.* More specifically, it starts with the nuclei of the usual isotopes of nitrogen and helium, ends with a free proton and a very unusual nucleus of oxygen. In Figure 11, the stem of the *Y* is the path of the alpha particle on its way to its rendezvous with death—death as an alpha particle, that is to say; the thin tine of the fork is the path of the newborn proton, the thick tine is that of the newborn nucleus of oxygen 17. You look in vain for the track of the target nucleus of nitrogen 14, since before the collision it was just the nucleus of an ordinary atom going peaceably about its business.

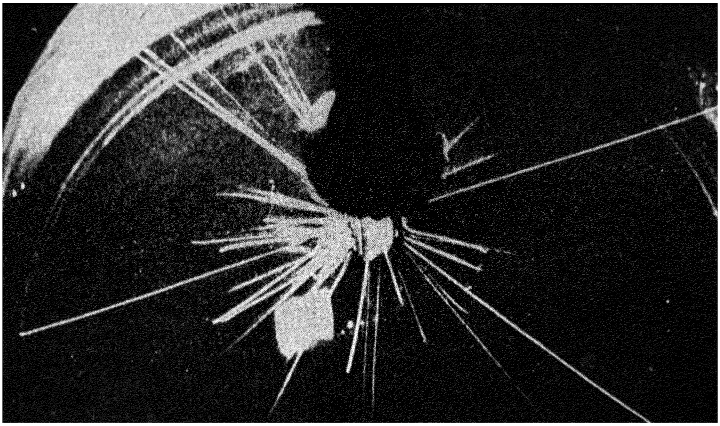


FIGURE 10

The man who engineered this transmutation was Ernest Rutherford. You may have noticed that I have rarely given names in these discourses. It is one of the most amiable traits of scientists that they are normally very meticulous in giving credit to others, even to the extent of marring their own expositions by their laborious efforts to hand a bouquet to everyone who deserves even a flower. This acme of fairness is not without disadvantage, and in lectures like these it is wiser to apply the unfairness of silence to everyone equally. However, in this field there is, or rather until he died ten years ago there was, a man so outstanding that none wished to deny his preeminence, the pioneer who opened up the way which all the rest have followed. Around the turn of the century, he established the nature and the laws of radioactivity. About 1908 he invented the nuclear atom-model which was expounded at the opening of these lectures, though in this he was not alone. For the next ten years he explored the force fields by which the nuclei control their planetary electrons, and finally with the alpha particle he crashed through to the nucleus itself, violating for the first time the hitherto inviolable elements.

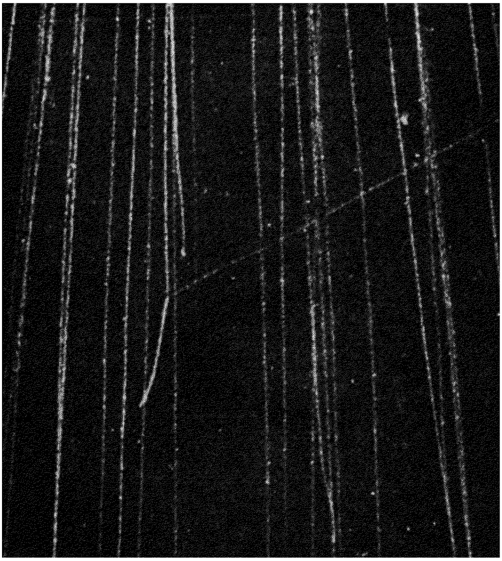


FIGURE 11

That was transmutation, and Ernest Rutherford achieved it first in 1919.

There is a story of Rutherford which I borrow from President Compton of the Massachusetts Institute of Technology. Compton in 1918 was a scientific liaison officer in Paris, where he attended a conference convoked to discuss some problem of warfare. Rutherford had been invited, but shortly before the conference there arrived a letter or a telegram, in which he said, "I shall not be coming, as I think I have split the atom of hydrogen, and this if true is more important than any war." This story becomes even more striking when we realize, as Rutherford never did, that he was opening the way to victory in a war of even greater magnitude which he was never to see. Actually it is not known what he thought he had observed; probably he was temporarily on a wrong track, but by 1919 he came upon the right one.

It is interesting also to reflect upon the manner of his discovery. The protons resulting from his transmutations were few, and they made faint sparkles or glints on a phosphorescent surface on which they were allowed to impinge. It took good eyesight to discern these feeble glitters (I am told that every graduate student who came to Rutherford's laboratory was tested to find out whether his eyes were good enough to distinguish them, and many were rejected.) Also it took a rested or dark-adapted eye, and the investigators sat in total darkness for an hour before they set to work. How strange to think of these people staring into the darkness at ghostly evanescent flickerings, unwittingly beholding the dim precursors of what was later to develop into the colossal atomic energy installation and the formidable bomb!

There is another agent of transmutation which I must briefly mention. It is the corpuscle of light. The corpuscles of light have not received their due meed of attention in these lectures, and alas they never will, for there is too much else to say. I use the word "light" in the general sense, including not only the visible light by which we see, but also and primarily the x rays and the gamma rays, which are of the same nature as visible light and differ basically in the energy of their corpuscles. The energy of a corpuscle of light can be measured very simply. We allow the corpuscle to fall upon the surface of a metal, and it ejects an electron. The electron has all the energy of the corpuscle, except for a few electron volts of which we can take account if it is worth while (usually it is not). Thus by measuring the energy of the electron we obtain the energy of the vanished corpuscle of light and that of all other corpuscles which are of the same kind.

Suppose now that a flock of deuterons is bathed in a beam of light consisting of corpuscles all having the same energy. If this energy is, say, 2.30 Mev, it is found that some of the deuterons are parted into their elementary components, the proton and the neutron; and the kinetic energies of proton and neutron add up to 0.12 Mev. This shows that it takes just 2.18 Mev to unbind the deuteron, the surplus, if any, becoming kinetic energy. We test the conclusion by shifting to a beam of light containing corpuscles of energy, say, 2.20 Mev; now we find the proton and the neutron sharing a kinetic energy of 0.02 Mev. We clinch the conclusion by shifting to a beam of light of which the corpuscles have lesser energy than 2.18 Mev; and, however little they may fall short of this critical energy value, they never are able to unbind any deuteron at all. Now, 2.18 Mev corresponds, by Einstein's relation, to the mass deficit 0.0023 of the deuteron. The wheel has come full circle, and the fundamental premise has been proved.

There is still one more important agent of transmutation, and this one is the mightiest of all. It is the *free neutron.* I shall be spending most of the rest of my time in talking about its deeds and misdeeds, but first we must return to the alpha particle for a very special reason which is relevant to what follows.

I told you that the deuteron and the proton, when they are to be used as agents of transmutation, must be accelerated to high speeds and high kinetic energies with the aid of a high-voltage machine. I never did tell you the exact amount of kinetic energy which they require. This varies from case to case, that is, from one reaction of transmutation to another, and also the lower limit is hazy. Let me merely say that for some reactions, including the first one I described, half a million electron volts or even less may suffice to get an ample supply of newborn nuclei; but for most it is necessary to ascend into the millions. Well, the alpha particles *are* up in the millions. Those which Rutherford used had, in many cases, 8 Mev of kinetic energy. By omission I led you to believe that he must have had a high-voltage machine, and a good one. But he had not; there was no such thing at the time. For accuracy I ought to say that, owing to its double charge, a free helium nucleus can be converted into an 8-Mev alpha particle by a *four*-million-volt machine. However, even a four-million-volt machine was utterly out of the question in 1919; it would have been as far beyond the then-attainable as a V-2 rocket or a jet-propulsion plane. How, then, did Rutherford get his 8-Mev particles when he had practically no voltage at his command?

He got them because Nature gave them to him, newborn and complete with their kinetic energy.

This is an instance of *radioactivity* of a rather special kind. There are about twenty-five sorts of nuclei which are called "alpha emitters" because every now and then one of them will emit an alpha particle. This is a perfectly spontaneous event. It is not due in the least to the intervention of man, who indeed can do nothing to help or to hinder it.

All of these twenty-five-odd nuclei are in the latter half of the Periodic Table, into which incidentally we are now moving, bag and baggage; we shall concern ourselves from now on with the heavy elements almost entirely. It would do little good to burden your memories with the names of the twenty-five, but one of them is radium itself, and another is called *polonium*. Polonium was the first of the radioactive elements to be isolated by the chemists, apart from a few which are both weak in radioactivity and abundant in Nature. Polonium also has supplied a good many of the alpha particles employed in experiments of transmutation. These features justify me in choosing it for my example.

Polonium is an isotope of the element 84. All nuclei of this element have 84 protons, and the polonium nuclei are those which have 126 neutrons in addition, making a total of 210 elementary particles or nucleons. What happens to polonium is symbolized by the formula

$$_{84}\mathrm{Po}^{210} \rightarrow {}_{2}\mathrm{He}^{4} + {}_{82}\mathrm{Pb}^{206} \quad (8\ \mathrm{Mev})$$

The nucleus of polonium separates itself into an alpha particle and a "residual" nucleus which belongs to an isotope of lead. The Latin word for lead is *plumbum,* and this is why the symbol is Pb. The two nuclei have between them about 8 Mev of kinetic energy.

This spontaneous sundering is a rather mysterious affair, but no longer nearly so mysterious as it appeared at the time of its discovery half a century ago. To begin with, we now know that the 8 Mev of kinetic energy implies that the mass of these 84 protons and 126 neutrons is greater by no slight amount—0.0085 mass unit—when they are clumped down into one great nucleus than when they are clustered in two smaller nuclei. This was unguessed in the early days of radioactivity, when people speculated almost endlessly about the source of this strange outpour of kinetic energy. But it seems also to contradict what I told you earlier, to wit, that the nucleons lose mass when they are clumped together. How can it be that they should lose more mass when they are divided between two smaller clusters than when they are packed into a single big one?

We think that we know the answer to this question. To picture it, I show (Figure 12) a drawing of a cross section of a polonium nucleus, from which the inner particles have been left out to spare the draftsman needless trouble. Consider two protons on opposite sides of the nucleus. I have said that protons attract one another with a short-range force and repel one another with a long-range force. Now, this nucleus is so fat that when two protons are on opposite sides of it, they are out of range of one another's attraction but still *in* range of one another's repulsion. True, each of them is sticking tightly to its nearest neighbors, and these in turn are sticking tightly to *their* nearest neighbors, and thus by intimate forces the whole nucleus coheres together. But if we consider by itself the interaction between these two distant protons, we see that it contributes what I may term an explosive factor to the nucleus, which the nearest-neighbor attractions are obliged to offset. Now suppose that the nucleus disintegrates in the way which our latest formula describes. We may imagine that the two distant protons are now cuddled up together in the alpha particle, where they are much closer together than they were before, and the short-range attraction is able to offset the repulsion by an ample margin. It follows that the two smaller nuclei are, as we say, *more tightly packed* than the great one; they have a larger binding energy and a larger deficit of mass. Thus, the emission of an alpha particle is a consequence of the fact that within the nucleus there is competition between short-range attractions and long-range repulsions. This is our answer to the question. It may not be the full answer, but it looks adequate, and as yet we are not required to seek further.

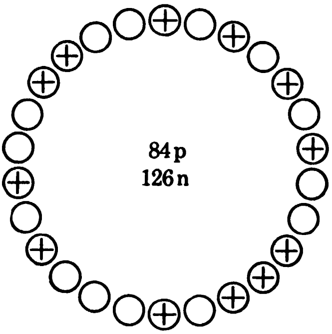


FIGURE 12

There remains another great question. Why does not this explosive alpha-particle emission take place the very moment the polonium nucleus is created? Why, indeed, is there any polonium on earth? The books tell us that the half-life of polonium is 136 days; and by this they mean that, of all the polonium nuclei now in existence, one half will still be unex ploded 136 days hence, one half of the remaining half will still be with us 272 days hence, one half of the remaining quarter will still be extant 408 days hence, and so on and on. Why do they wait so long before they yield to their hearts' desire and dissipate their mass in other forms of energy?

We think that we know the answer to this question also; but it is a secret. Not, I hasten to add, a military secret, but what I may term a *quantum-mechanical* secret, veiled from all but those who are willing to spend years in the study of the abstruse subject of quantum mechanics, which is the current name for the basic theory of physics. Let me leave this secret for the initiates and pass rapidly onward to the climax.

Imagine that you are able to do something which neither you nor anyone else will ever be able to do, that is, to take a super-microtome or a super-razor blade and cut this great nucleus of polonium into two neat halves like an orange. You will then have two nuclei, each of 42 protons and 63 neutrons. Would these two have between them a *lesser* mass than the original great nucleus, so that at the moment of your slicing some of the rest mass would be converted into other forms of energy, and the two halves would fly madly apart? Or would they have between them a *greater* mass than the original nucleus, so that you would have to do work and provide energy in addition to the miraculous razor blade and the miraculous skill wherewith to use it?

The former answer is indicated by the argument which I used in connection with alpha emission. The protons will on the average be closer together in the half-size nuclei than in the big one, and this suggests that, owing to the short-range attractions prevailing over the long-range repulsions, the half-size nuclei will be more tightly packed and have a lesser mass.

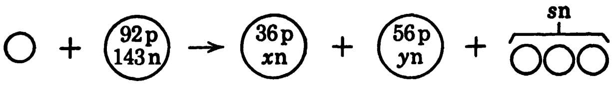
However, there seems to be a weakness in this argument. It is too all-embracing. It applies, in fact, equally well to all the other massive nuclei. Now, the other massive nuclei comprise such sound and stable elements as gold and lead, tantalum and tungsten, iridium and platinum. These have been under scrutiny for a long time, and have yet to exhibit the slightest sign of instability of any kind whatever. When an argument leads to the paradox that gold and lead must be unstable, one feels that there is something wrong with the argument. And yet it is a shocking fact, derived from all that we know and all that we can reasonably conjecture, that the argument is evidently sound. All the massive nuclei are heavier than their two halves would be, if by some miraculous skill we were able to cut them apart.

You grasp what this implies. It implies that all the massive nuclei have no right to be alive at all. Indeed, they should never have been created, and, if created, they should have blown up instantly. Yet here they all are, and the rocks of the earth are full of these little high-explosive clusters, all of them ready to separate into halves with transformation of rest mass into kinetic energy and other forms of energy. And, yet, they never do sunder themselves. Some inflexible inhibition is holding them relentlessly together. The nature of the inhibition is also a secret; but here I suspect that it is neither a military secret nor a quantum-mechanical secret, but one thus far reserved by Nature for herself.

This is not the time to be alarmed—not yet. The mercury in your thermometer, the platinum in your bracelet, the gold at Fort Knox are not going to explode. The inhibition is not going to pass away just because we know it is there. It is not going to break down unless and until we find some physical way to break it down; the lock is not going to open until we find a key; the genie will not escape from the bottle until we find a corkscrew. But it chances that somebody unwittingly did discover a way to dissolve the inhibition—not indeed in all cases, not even in many cases, but at least in the cases of uranium and plutonium and a few more. I think it fitting here to place another name by the side of Rutherford: it is Enrico Fermi.

Here in Figure 13 appears the process of "fission" or, rather, one of the many processes subsumed under that awesome name.

On the left stands the symbol of the nucleus "uranium 235," composed of 92 protons and 143 neutrons. It is ready to separate into two or more smaller pieces, with tremendous reduction in rest mass; but the inhibition holds it firmly together. The door is locked, the genie is confined in the bottle. But here, still further to the left, comes the key to the lock, the corkscrew to the bottle, the liquidator of the inhibition. It is a free neutron, just such a one as we get when we smite one deuteron with another deuteron. Nothing hinders its advance to the uranium nucleus. If it were a proton or a deuteron or an alpha particle, it would be repelled by the powerful electric charge on the uranium nucleus, and all our voltages could scarcely drive it thither. But it is a chargeless particle, and the electric barrier is unavailing against it. The neutron glides unhindered through the barrier, and the nucleus sucks it in, and then the whole of the complex nuclear structure goes to pieces.



$$x + y + s = 144$$

Conversion of circa 0.2 mass unit of rest mass into circa 200 Mev of other forms of energy

FIGURE 13

On the right stand the symbols of the pieces. First, there is a nucleus comprising, for instance, 36 protons, which is a nucleus of the thirty-sixth element of the Periodic Table, the element *krypton.* The 36 protons are not the whole of this nucleus; there are also a lot of neutrons. Then, there is a nucleus comprising the other 56 protons, and this nucleus belongs to the element *barium;* it too comprises a lot of neutrons. I have indicated that the krypton nucleus has x neutrons and the barium nucleus y neutrons. This is not because the values of x and y are secret; it is because there are many varieties of fission, and x and y are not the same for all. The best statement that can be made in a few words is, that x is somewhere around 65 and y is somewhere around 80. The sad thing is that the sum of x and y is not quite equal to 144. Some neutrons are left over, totally free. I have denoted their number by s, because it also varies from case to case. The sum of x and y and s is always 144, the number of neutrons in the former uranium nucleus plus the one which sowed the wind; but, subject to this condition, the individual numbers vary. Even now I have not exhausted the variations on the theme: for it is possible for the uranium nucleus to divide itself so that the major pieces comprise 35 and 57 protons respectively, or 37 and 55, or 38 and 54—any of some twenty pairs of numbers, each of the pairs, however, adding up to 92 so that all the protons belong to one nucleus or the other.

Fission therefore is the name of many processes, and not the name of only one. But all of these have the same feature in common: the great conversion of rest mass into kinetic and other forms of energy, the great "release of energy" as it is briefly called. The dissipated rest mass amounts in fact to about 0.2 mass unit, which is little short of 200 Mev. This is about eight times the energy release that occurs in that other reaction which long held the palm, the reaction of lithium six with deuterons to form a pair of alpha particles. Most of this energy appears in the form of kinetic energy of the two major pieces and the neutrons which are freed; however, some apparently escapes in corpuscles of light.

But an eightfold rise in the energy release, though big in itself, should not be catastrophic. Why is it that no one beyond a few specialists ever heard of the lithium-and-deuteron reaction with its twenty-odd million electron volts of converted rest mass, and now everyone is appalled by the atomic bomb in which the release is not even tenfold greater?

The answer is provided by the s free neutrons. But, in order to introduce it, I ought to mention the low "efficiency" of the transmutation process. It has been stated that when we fire a deuteron at a nucleus of lithium six, we *may* get a reaction in which 0.024 mass unit of rest mass becomes 22 Mev of kinetic energy. The accent, however, is on the *may*. To be sure of achieving this reaction, we should have to take careful aim. But the drawback is that we cannot take aim at all. There are no William Tells in the laboratory of nuclear physics, and nobody can draw a bead upon a nucleus. The best we can do is to project a great stream of deuterons upon a great block of lithium and hope that we shall make some lucky hits. It turns out that, by and large, we can make about one lucky hit in a million. Remember that each deuteron has to receive about half-a-million electron volts of energy from your high-voltage machine. As long as you think only of the lucky deuteron that returned a twenty-million-volt profit on your half-million-volt investment, it looks like a wonderful power plant. But when you think about the other 999,999 deuterons, on every one of which you lavished the same investment which they then proceeded to fritter away while rambling uselessly around inside the block of lithium—when you think of these, it may still look like a good gamble if you are sufficiently interested in the singular result of the lucky hit, as many physicists are; but, as a power plant, you see that it is nothing.

The same could be said of the reaction of uranium with neutrons, were it not for those s free neutrons which spring forth from the fissions. It is they which make all the difference in the world, and all the difference *to* the world. Maybe we did waste a million neutrons, or a billion, before we got the first fission. But now it does not matter much, because one of s neutrons from that fission is able to provoke the fission of another uranium nucleus, and one of *its* fresh neutrons is able to provoke a third fission, and so forth with ever-gathering and cumulative plenty. The first successful neutron started a chain of fissions, and all the energy released in all the innumerable links of the chain goes to the credit or discredit of that single neutron. Now it *is* a power plant which we have, or, if the chain develops rapidly enough, it is a bomb. This is the *chain reaction,* a word as frightful to some of us as the thought of the end of the world to some of our ancestors of old.

Here is the climax of my lectures, and here is where you should be frightened; and, if I had an orchestral accompaniment, here is where the orchestra would have mounted to a tumultuous fortissimo, with the drums rolling and the trumpets blaring and the tuba groaning and the strings in a frenzy, and whatever else a Richard Wagner could contrive to cause a sense of *Götterdämmerung;* for, let there be no doubt of it, this *is* something that could bring on the twilight of civilization. But at this crucial juncture I have only words to serve me, and all the words are spoiled. We speak of an awful headache, a dreadful cold, a frightful bore, and an appalling storm; and now when something comes along that is really awful and dreadful and frightful and appalling, all these words have been devaluated and have no terror in them. I have to fall back on the saying, of unknown origin and dubious value, that the strongest emphasis is understatement. Let then this picture, with its circles and its symbols and its numbers, be considered an emphatic understatement of the most terrific thing yet known to man.

4.

WE PROCEED with some questions bearing on the chain reaction and on the fission process to which it is due.

Why has not the chain reaction occurred of itself long ago, wiping out all the uranium 235 on earth if not the earth along with it?

It might be thought that the salvation of the earth was due to the absence of free neutrons, since the free neutron is something which the physicist obtains by transmutation—either by the transmutation of two deuterons into helium 3 and a free neutron which has already been described, or by any one of scores of other reactions which likewise liberate neutrons. However, there are free neutrons among the cosmic rays, and we must deem it certain that every now and then during the geologic ages a nucleus of uranium 235 has suffered fission. Why, then, has none of these fissions developed into a chain reaction?

The first of the reasons is that in the rocks the uranium nuclei are surrounded by an enormous number of neutron traps in the form of nuclei of other elements: oxygen and calcium and magnesium, and others which a geologist could list more readily than a physicist. Now, neutrons have a great liability to "capture" or annexation by a nucleus—by almost any kind of nucleus. Often a wandering neutron bounces off a nucleus which it encounters and continues its roamings; but sooner or later it coheres with a nucleus, and that is the end of its story as a free neutron, unless and until some physicist strikes the nucleus with an appropriate projectile and releases the neutron again. (Incidentally the binding energy which is set free at the instant of capture usually goes off in the form of a corpuscle of light.) When, therefore, a nucleus of uranium 235 suffers fission while embedded in the rocks, its liberated neutrons enjoy but a brief vacation of freedom, and then are caught and rendered harmless by the adjoining nuclei.

But the chemists purified uranium a century or more ago and have doubtless made a good many bricks of solid pure uranium and a good many jars of uranium powder. Why then has none of these ever been known to explode?

The reason is again the same, though more specialized. "Natural" uranium is a mixture of several isotopes, of which all but two are too rare to matter. These two are the sinister isotope 235, and another which is 138 times as abundant. This other is uranium 238, of which the nucleus is composed of 92 protons and 146 neutrons. The situation at this point is confused by the fact that uranium 238 is itself liable to fission, not, however, nearly so much so as the sinister isotope; the key which the neutron holds does not fit the lock so well, the inhibition is not nearly so readily dissolved. In the mixture of isotopes which is natural uranium, each of the dangerous nuclei is surrounded by 138 others which serve primarily as neutron traps and, by so serving, do much more to frustrate the chain reaction than their occasional fissions do to spur it. The abundant isotope acts as a brake which Nature herself supplied, keeping the chain reaction from running away, however large and however pure a piece of uranium the chemists may contrive to isolate.

Man, however, succeeded in loosening this brake by *separating the isotopes of uranium.* This is a task of a much higher grade of difficulty than the separation of two different chemical elements. Two different elements may be separated by chemical processes; this in fact was the original definition of "element." But the isotopes of uranium have the same chemical properties—this in fact was the original definition of "isotope"—so that chemical methods are unavailing. The problem was one of those attacked by the famed Manhattan Project, which spent upon it no inconsiderable fraction of its time and its resources. That the problem was not invincible was proved by the bombs themselves.

However, although the art of separating the uranium isotopes on a grand scale was an achievement of the war, the art of separating them on a small scale was already well known. I saw myself in 1940 what was probably the largest amount of uranium 235 ever isolated till that time. It was a transparent brownish film on a glass plate, hardly more than such a smudge as one might obtain by blowing a few puffs of cigarette smoke against the glass. Nevertheless it was pure uranium 235; why did it not explode when the physicists exposed it to a stream of neutrons?

The answer to this question is one word, and the word is *leakage.* The chain reaction never started in the film because too many of the neutrons which were released by the occasional fissions made their way to the surface of the film, escaped from the film, and never came back. This leakage, the last of the brakes imposed by Nature on the chain reaction, must be diminished by making the dangerous metal stout and thick. No conceivable shaping of the tiny amount of the metal in the tenuous film could have reduced the leakage low enough to bring about the chain reaction. But as the size of a mass of uranium 235 of any reasonable shape is magnified, the volume increases in greater proportion than the surface; and there is a "critical size" at which the leakage no longer counterbalances the trend toward the explosion. The nuclear bomb miscalled atomic is made by putting together two blocks of metal each of which is of less than the critical size, while conjointly they form a block which during its very limited lease of life is of size greater than the critical.

The value of this critical size is a secret, and this time the secret *is* a military one, not a quantum-mechanical one nor one successfully reserved by Nature for herself. We all know, however, that it is not too great a size for a single aeroplane to carry. With these remarks I turn away from the horrendous topic of the atomic bomb, except for one allusion yet to come. We will now attend to matters of less immediate but more permanent concern, destined to endure after the bomb, as we all hope, shall have become no more than an evil memory.

The bomb is a device in which the chain reaction is uncontrolled and uncontrollable. There is a device in which the chain reaction is controllable and is controlled. It bears a name already old in physics. A century and a half ago, Alessandro Volta discovered or invented (in science, it is often impossible to distinguish between these words) the earliest source of continuous electric current. He called it a "pile," because in his version it was a pile of metal strips and acid-moistened cloths. The name survives in the Romance languages, though in ours it has been replaced by "battery." The pile or battery was a milestone in the history of science and of engineering, the first agency whereby chemical energy could readily and steadily be converted into utilizable power. Now, a hundred and fifty years after Volta, there is another pile. It also is a milestone in the history of science and of engineering, the first agency whereby nuclear energy can readily and steadily be converted into utilizable power. When in the days of secrecy I heard the name in its new meaning and knew that Fermi an Italian had invented the new pile, I took it for granted that he had intentionally chosen the appellation of Volta. Great was my surprise when I learned from Fermi that it was mere coincidence. He had conferred the name on his device because it was "such a big pile of graphite and uranium."

Graphite is elementary carbon, the sixth element of the Periodic Table, of which nearly all the nuclei consist of twelve fundamental marbles, half neutrons and half protons. The uranium of the pile is "natural" uranium, with its normal great preponderance of the isotope 238 over the isotope 235. The separation of the isotopes is circumvented. To explain how that hard and costly process is made needless by the presence of the graphite, I must give one more fact about fission.

The fission of uranium 235 is much more readily accomplished by slow neutrons than by fast ones. We need not search far for a reason: the impetus of a hurrying neutron carries it safely through the danger zone of attraction surrounding a nucleus, the sauntering neutron is drawn in. Now, the newborn neutrons fresh from fission are fast-moving. Velocities are seldom stated by nuclear physicists, not for want of the ability to measure them, but because the values of kinetic energy are generally more useful. The newborn neutrons start out with several million electron volts of kinetic energy and are moving far too fast to serve efficiently as links in the chain reaction. Friction must be applied to take away their excessive energy and slow them down; and here we find friction reduced to its ultimate terms, which are impacts.

Each time a fast-moving neutron hits a slow-moving nucleus and bounces off, it leaves some of its kinetic energy behind and continues on its journey with a lessened speed. The lighter the nucleus from which the bounce occurs, the greater is the lessening of speed. A lightweight nucleus is therefore to be desired, and we think of the proton first of all. But protons have far too great an appetite for neutrons; and if a flock of fresh fast neutrons were to be admitted to a block of matter containing many protons, we should presently find ourselves in possession of a flock of deuterons formed by that very process of binding or cohesion which was described in Lecture 2. One lightweight type of nucleus after another was considered and discarded, for this reason or another; and carbon proved in practice to be the best of "moderators," meaning that it came nearest to the ideal of treating with the neutrons by moderating their speeds and not trapping them too soon.

The pile, then, consists of rods of natural uranium embedded in a matrix of "moderator" graphite. Fission occurs in the rods; the fast neutrons emerge into the graphite, ramble around, are slowed down, and in the course of time return to the uranium with their speeds reduced to values which make them apt for provoking further fissions. Now the chain reaction may proceed; not, however, unless the pile surpasses a certain crucial size, for otherwise the leakage of the neutrons through its surface is too great.

During the summer and fall of the year which followed Pearl Harbor, an enterprise of great moment was under way in utter secrecy, beneath the concrete bleachers of the football field of the University of Chicago. A pile, the first of its kind, was coming into being. The provision of uranium and graphite was arriving in stages, and therefore the pile was growing by stages up to the critical size. Neutrons were fed to the pile from an external source whenever they were required. Embedded in the pile, a neutron detector reported how many neutrons were circulating in the mass. The bigger the pile, the bigger the reading of the detector; the fission process was magnifying the number of the neutrons supplied from without. Yet, whenever the external source of neutrons was shut off, the reading of the detector fell promptly to nothing: the chain reaction had not got its start.

At last the pile had grown so great that the theory—or perhaps it should be called a well-founded conjecture—indicated that it had already passed the crucial size. But if the conjecture was correct, why was the proof not given then and there by evidence of a terrible kind? Well, a precaution had been taken. In the pile there were transverse tunnels or slots, and in these slots there were strips of the metal called *cadmium*. I have said already that there are many elements the nuclei of which attract and capture and annex the free neutrons which pass near them. Among all elements, cadmium is one of the most voracious for slow-moving neutrons. When the neutrons in the pile leaked into one of these tunnels, the cadmium swallowed them up, and that was their finish; the chain reaction never had a chance. The pile was kept safe by the brake which the cadmium strips provided against the runaway. But the cadmium strips could be drawn out of the tunnels, and the theory or conjecture said that if they were—but here I ask Fermi to take over the story.*

"On the morning of December second, 1942, the indications were that the critical dimensions had been slightly exceeded and that the system failed to chain-react only because of the absorption of the cadmium strips. During the morning all of the cadmium strips but one were carefully removed: then this last strip was gradually extracted, close watch being kept on the intensity. From the measurements it was expected that the system would become critical, by removing a length of about eight feet of the last strip. Actually when about seven feet were removed, the intensity rose to a very high value but still stabilized after a few minutes at a finite level. It was with some trepidation that the order was given to remove one more foot and a half of the strip. This operation would bring us over the top. When the foot and a half was pulled out the intensity started rising slowly, but at an increasing rate, and kept on increasing until it was evident that it would actually diverge. Then the cadmium strips were again inserted into

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* As he told it in the *Proceedings of the American Philosophical Society,* 1946.

the structure, and the intensity rapidly dropped to an insignificant level."

On hearing this news, Arthur Compton telephoned to James Conant. Compton was the director of the enterprise at Chicago; Conant, the chairman of the Office of Scientific Development and Research. Compton said: "You will be interested to know that the Italian navigator has just landed in the new world. Due to a slight miscalculation, the earth was smaller than he had supposed, and he arrived a few weeks earlier than he had expected. He landed on the shore at noon today." Conant answered: "Marvelous! Did he find the natives friendly?" Compton replied: "The natives received him gladly as he had expected. Everyone landed safe and happy." *

December second, 1942, is one of the crucial dates in the history of the world, and not altogether nor even chiefly because of the bombs which were to follow. The pile is our reliance for the provision of nuclear energy miscalled atomic for the purposes of peace. The purposes of peace demand a controllable supply of nuclear energy passing through the form of heat into the form of energy electrical or mechanical. The energy of rest mass, becoming first of all kinetic energy of the fragments of the fissile nuclei, is passed along by these in smaller and smaller driblets to the other atoms of the pile. Soon the energy is dispersed among the atoms of the entire pile, a tiny bit to each; and this dispersion makes it heat. Heat thus arises in the substance of the pile itself; and the cadmium strips provide the control.

The conversion of heat into other useful forms of energy is the task of the engineer. It falls beyond the field of physics as commonly defined, and far indeed beyond the scope of these lectures. It is no secret that the United States Atomic Energy Commission has accepted this task as one of its obligations. Estimates have been made of the probable cost of the power thus to be generated, when all the technical problems shall have been solved. All such prophecies are risky, but this one

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* Various wordings of this famous conversation have appeared in print. This one has Compton's imprimatur, for which I am indebted to him.

seems as nearly riskless as good judgment can ensure. It is concluded that for a large power plant in a city of the northeastern seaboard of the United States, power derived from uranium would be somewhat more expensive than power derived from coal; yet not so much more expensive that the balance might swing the other way, should coal become somewhat dearer or the art of producing nuclear power somewhat less difficult than is currently foreseen. Among other implications, it follows that even now there are regions of the world where nuclear power would be cheaper than power derived from coal, were the technical difficulties—and the political difficulties!—already overcome. It is rather a surprise to find Britain already classed among these regions in the lately published opinion of a very eminent British physicist.

The heat of the great piles of wartime, which were constructed in Washington State and Tennessee after the "pilot pile" of Chicago had proved that they would work, was carried away by the Columbia River and the Tennessee River. However, it was not for the purpose of warming up these rivers that the piles were set up. They had a purpose altogether different; but to understand it we must enter on the last main topic of these lectures, the topic of *radioactivity.* We have already noticed one, and the rarer, kind of radioactivity, which consists of the emission of alpha particles. A commoner and a very different kind will now engage our attention.

In preparation for this topic, we reproduce here Figure 3.

			$Q_{\mathrm{M.U.}}$	Q_{Mev}	Q/N
$_0n^1$	○	1.0089	0	0	0
$_1H^1$	⊕	1.0076	0	0	0
$_1H^2$	⊕○	2.0142	0.0023	2.18	1.09
$_1H^3$	⊕○○	3.0165	0.0089	8.3	2.8
$_2He^3$	⊕⊕○	3.0160	0.0079	7.4	2.5
$_2He^4$	⊕⊕ ○○	4.0028	0.0302	28.1	7.0

Here at the top stand the two fundamental marbles, and beneath them the four simplest of the composite nuclei, three of them already familiar to us. The first of these is the deuteron, composed of two elementary particles, one of each kind. We can readily imagine two other composite nuclei of equal simplicity, one composed of two protons and the other composed of two neutrons. Yet neither of these has ever been observed; and so eagerly have they been sought, such a feather would it be in the cap of any physicist to find them, that we may pretty well take it for granted that neither exists. No more does any larger nucleus exist which is made up exclusively of protons or exclusively of neutrons. It is clear that there is some peculiarity of the nuclear attractions whereby two or more protons cannot cohere together without the aid of one or more neutrons, and *vice versa.* This is a very peculiar peculiarity indeed, and nothing will be gained for our present purposes by attempting to describe it otherwise than by its result.

Next come two nuclei with three particles apiece. One of them is our now familiar nucleus ${}_2He^3$, with two protons and one neutron. This is a unique nucleus, the only stable one which has more protons than neutrons. The other is ${}_1H^3$, consisting of two neutrons and one proton; we shall presently meet it again. These nuclei are called *isobars* of one another; isobars have the same number of nucleons, differently divided between protons and neutrons.

Next comes the alpha particle, consisting of two protons and two neutrons. This and the deuteron are two examples of a rather rare type of nucleus in which neutrons and protons are equal in number. There are only a dozen of these which are stable, and the last is the one with twenty protons and twenty neutrons.

All other nuclei are richer in neutrons than in protons, and, as we advance along the Periodic Table, the neutron excess becomes greater, both relatively and absolutely. We have already made the acquaintance of uranium 238, with its 92 protons and no fewer than 146 neutrons, a neutron excess of 54, amounting to over 58 per cent. This is pretty close to the extreme.

To summarize all this in the form of a principle: let us consider any arbitrary number of nucleons—call it M—bound together into a nucleus. There will be one particular distribution of these nucleons as between protons and neutrons, which is the only stable one. (For accuracy it is necessary to admit that for a few values of M there are two stable distributions; this occasional anomaly need not distract us.) For a few of the lighter nuclei, but for none of which M exceeds 40, the stable distribution is half neutrons and half protons, $M/2$ of each. For one and only one, the stable distribution comports more protons than neutrons. For all the rest the stable distribution comports more neutrons than protons, and the excess of neutrons trends upward with increasing value of M.

Each agglomeration of nucleons then has one special desired proton-and-neutron balance in which alone it is stable and happy. Yet by transmutation the physicists are able to make many an agglomeration which has a wrong value of its proton-neutron distribution—wrong in the sense of not being the stable one. In particular, many nuclei can be produced which have one neutron too many and one proton too few. How does such an unhappy nucleus identify itself and act?

Such an unhappy nucleus adjusts itself to its desire by spontaneous conversion of a neutron into a proton. The dissatisfied, unstable isobar becomes the satisfied and stable isobar. Our nucleus ${}_1H^3$ is such a one, and it seeks and finds stability by changing itself into ${}_2He^3$.

This is easily said, but more than this is required. The neutron must acquire one unit of positive charge. Conceivably it might pick one up, but positive charges are not rambling around in space and waiting to be caught. Conceivably also it may eject one unit of negative charge, which comes to the same result as far as its charge is concerned. This it usually does. It ejects a negative electron; and having done so the neutron has become a proton, and the nucleus is satisfied, temporarily at least.

In Figure 3 the masses of ${}_1H^3$ and ${}_2He^3$ are given as 3.0165 and 3.0160. To the same "degree of approximation"—that is, when stopping four places to the right of the decimal point—the rest mass of the electron is 0.0005. It appears that the extra weight of the unstable nucleus is just the weight of the electron which it ejects! On pursuing exactitude one stage further, it is found that just a little mass is left over—the equivalent of 0.012 Mev; and this turns up as kinetic energy of the newborn electron, a sort of dowry. This is, however, a very parsimonious case. With most unstable nuclei, the dowry is very much larger, and the electron emerges with kinetic energy several or many times greater than its rest mass. This means that the mass difference between the unstable and the stable isobar is several or many times as great as 0.0005.

A famous example of instability is provided in the pile; and here comes my last allusion to the atomic bomb.

It has been said that a nucleus of uranium 238 is capable of capturing or trapping a free neutron. When this event occurs, as it frequently does in a pile, there comes into being a nucleus of 239 nucleons, 92 of which are protons and 147 are neutrons. This is uranium 239, and it is an unhappy nucleus. I doubt whether any theorist could have foretold its discontent; but its behavior proves it. It ejects an electron—not immediately, but sooner or later—and becomes the isobar possessing 93 protons and 146 neutrons. Now a new name is required; for it has become a nucleus of the element standing in the ninety-third place of the Periodic Table, and this element was unknown until it was created by affording to uranium 238 the chance of capturing neutrons. The name is *neptunium*. But even now the nucleus is still unhappy. Sooner or later it ejects a second electron. Now it is composed of 94 protons and 145 neutrons. Again a new name is required, for the ninety-fourth element of the Periodic Table was unknown until it was created by starting this chain of events. The name is *plutonium*.

Plutonium 239 is the second of the sinister nuclei. It shares with uranium 235 the rare and singular susceptibility to fission by slow neutrons. The inhibition is relaxed too readily, the cork comes out too easily, the key fits the lock too well. Plutonium is fit for the making of atomic bombs. Moreover it is relatively easy to make pure, for being born in the uranium of the pile and yet of a different chemical nature, it can be separated by the processes of chemistry. A pile is an instrument of two functions. It makes plutonium and it makes heat. In wartime, the plutonium was desired and the heat was a nuisance. Everyone concerned with piles now hopes that the time will soon come when the plutonium will be a nuisance and the heat will be beneficent. The sword will not become a plowshare, but the sword will be buried and the heat will operate the plow.

No name for this diabolical element could be fitter than plutonium, and yet we owe this aptest appellation to a mere coincidence. Uranium is element 92, and Uranus is the third from the last of the planets. Neptune is the second from the last of the planets, and therefore neptunium was chosen as the name of element 93. Pluto is the last of the (known) planets, and thence comes plutonium. The alpha particle, the original agent of transmutation and the cornerstone of nuclear physics in more senses than one, owes its appropriate name equally to the hand of chance. Rutherford identified three kinds of rays coming from radioactive bodies and named them after the first three letters of the Greek alphabet. The helium nuclei luckily received the letter alpha. The beta rays are the electrons of which I am currently speaking. The gamma rays are corpuscles of light due to internal changes in the nuclei, of which my time leaves me no room to speak.

Uranium 239 and neptunium 239 are by no means the only discontented nuclei which the pile produces in abundance. I recall now Figure 13 and the division of the uranium nucleus ${}_{92}U^{235}$ into a pair of nuclei lying midway in the Periodic Table, of which a nucleus of krypton (36 protons and x neutrons) and a nucleus of barium (56 protons and y neutrons) were taken as an illustrative pair. I repeat that uranium 235, a contented nucleus, has a great excess, a 58 per cent excess, of neutrons over protons. If these neutrons were to distribute themselves so that the resulting nuclei of barium and krypton had each a 58 per cent excess of neutrons over protons, these nuclei would be very unhappy indeed; for in the middle region of the Periodic Table the stable nuclei have a neutron excess of only some 40 per cent. If the uranium neutrons were so to distribute themselves that one of the nuclei of the pair was stable, the other would be all the more unstable. The fact that a few of the uranium neutrons are released into freedom is not sufficient to alter these conclusions.

These fragments of the broken uranium nucleus are therefore violently unstable. It is not sufficient for such a nucleus to convert a single neutron into a single proton by emitting a single negative electron; this process must happen over and over again before the nucleus comes to stability. The functioning pile is therefore a welter of radioactive "fission products," for such is the generic name of all these nuclei resulting from fission, whether they belong to one or another of the pairs into which the nuclei of uranium 235 originally broke, or are descendants of members of these original pairs. Several hundred of them have already been identified, and there is no reason to believe that we have recognized them all. It is not even certain that we have correctly identified all the original pairs or discriminated in every case correctly between nuclei which belong to original pairs and nuclei which are descendants. The pile in any case is a beehive of radioactivity, and as such it is a most perilous neighbor, not to be approached and not to be operated except by "remote control" while the operators stand behind huge and ponderous shields. One of the greatest successes of the Manhattan District was the immunity of the personnel, achieved through the incessant supervision of radiologists, of biologists, and of physicians who prescribed the limits of allowable exposure and saw to it that these were not transgressed.

But even yet I have not mentioned all the potencies of the pile for making radioactive nuclei. It is possible to place a sample of any element whatever near or even in the pile and bathe it thus in such a flood of neutrons that many of its nuclei become enriched by the addition of a captured neutron. Now, a stable nucleus to which a neutron is added frequently becomes a discontented nucleus by reason of the addition. We have already seen an example of this rule: the nucleus uranium 238, stable except for a slight liability to alpha emission, captures an extra neutron, and now that it is a clump of 239 marbles instead of only 238, it is unstable, and by emitting an electron it converts itself into a happier isobar which belongs to a different element. This is not a universal rule. When a nucleus of carbon 12 acquires an extra neutron it continues to be satisfied and remains a stable isotope of its original element under the designation "carbon 13." The addition of yet another neutron is more than it can tolerate; the nucleus carbon 14 transforms itself into nitrogen 14. In many cases, however, the capture of a single neutron suffices for the making of a radioactive nucleus.

But why should we desire to multiply the radioactive nuclei, of which we have long since possessed enough varieties to instruct ourselves in their general laws and properties? Indeed we have already so many that the acquisition of yet more may seem to have become a rather pointless hobby. Of course we never know what curiosities the undiscovered may reveal, and this consideration by itself would justify the quest. Already the quest has achieved the extension of the Periodic Table. To it we owe all the four elements beyond uranium; and, also, before 1941 there were several gaps in the Periodic Table corresponding to undiscovered elements between hydrogen and uranium, and not a single one of them is vacant now. Every element from 1 to 96 is known and is available: most of them indeed in stable forms provided by Nature, some in unstable forms provided by Nature, but *all* of them in radioactive forms created by the artifices of the laboratory. If this success had no practical value at all, it would still be no mean achievement to have extended the system which Nature herself left unfinished.

The chemists have already seized avidly upon the opportunity of finding out the behavior of these elements newly created. The atom of neptunium, for instance, is a system of ninety-three planetary electrons revolving around a nucleus of charge 93. No chemist would ever have enjoyed the chance of ascertaining how such an atom comports itself in its association with other atoms of more familiar kinds had not the physicists made it by exposing uranium to neutrons and letting it come into being by capture of the neutrons. Unstable it is indeed, and nevertheless enduring enough so that its atoms can exhibit their chemical affinities before they change themselves into atoms of plutonium. And here comes one of the strangest things of all: their instability is an advantage, and a great one. No one can detect the presence of a stable element unless its atoms are present by the millions of millions; but, given the right apparatus, one single unstable nucleus can disclose its existence at the moment when it ejects its electron; and if there are a few millions of such nuclei wandering together through the vicissitudes of chemical reactions or the labyrinth of the animal body, those which emit electrons mark out the way which the survivors are following as the path of a hidden army might be marked out in the night if each expiring soldier were to set off a flare at the instant of his extinction.

Much more is known at present of the chemical properties and the biological properties of several radioactive elements available only in scant supply than is known of those of some of the stable elements available in abundance since the earliest days of chemistry. (But now that we are in possession of radioactive isotopes of all the elements, the unexpected and surprising disadvantage of the old-fashioned elements will soon be remedied.) Note the word "biological." The plant body, the animal body, the human body are laboratories of an amazing complexity and an amazing purposefulness, the crowded theaters of bewildering reactions countless in their variety. The scientists who deal with life will learn a great deal by introducing into these theaters the radioactive isotopes to serve as the reporters of the adventures which the stable atoms undergo. So will, in their respective problems, the practitioners of many another science; and the physicist, witnessing like a layman the applications of his wonderful new nuclei in many a field which he is unqualified to enter, will hope and will expect that in the fulness of time their benefits will offset the horror of the deadly bypath in which they were foredoomed to make the first spectacular showing of their prowess.

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