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# SCIENCE NEWS

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ATOMIC ENERGY NUMBER

*Edited by*

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and JOHN ENOGAT



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## EDITORIAL NOTE

THIS second issue of *Science News* is entirely devoted to the subject of Atomic Energy, which is indeed science news in its most spectacular form. For this one issue we have intentionally broken our policy of producing a miscellany ranging the whole of Science, because of the serious problems, political, military and moral, as well as scientific raised by the invention of the atomic bomb. The chances of survival of civilised life as we know it now may well depend on finding a way to ensure that this new force will never again be used for destructive purposes and scientists as well as others are deeply concerned with thoughts and hopes about these problems.

This collection of articles does not attempt to enter into this whole wide field, but covers only the technical and scientific questions. We have tried to tell the story of atomic energy in a form that will be interesting and understandable to the general reader who is not a specialist. It is a complex story of a long technical development and, while we have aimed at telling it in a way that requires little previous knowledge, we could not hope to make it easy reading or suitable for the reader who wants to skim through the book without effort or thought.

All the articles have been written by scientists who were working at Los Alamos at the time when the plans for the book were made. It was felt that, by choosing authors who could work closely together, we would have the best chance of getting the story told fairly uniformly, while each article could still be written by someone with special knowledge on that particular aspect of the subject.

We have tried to make each article self-contained, since different readers may want to concentrate on different parts of the subject. For this reason there is a certain amount of overlapping in the introductory parts of the articles to

avoid excessive cross-references. The subject index will help to find the explanations for terms or ideas not explained in each article. The first article contains a general survey of the whole field and forms the key to the rest. The articles on "Atoms, Electrons and Neutrons" and "The Tools of Nuclear Physics" explain the general background.

Some of the authors belonged to the American, others to the British staff. The choice was indiscriminate and in this way the collection reflects the very friendly and close collaboration which British scientists enjoyed in several parts of the Atomic Energy Project, and in particular in the isolated community of Los Alamos.

Secrecy rules still govern some of the technical information on this subject. The authors found these rules less troublesome in writing the articles than they expected. While they had to leave out some items that would have made the story more interesting, the rule mostly concerned technical information that would have had no place in this non-specialist treatment.

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Next *Science News* 3 returns to the usual collection of long and short articles on various subjects, including "Scientific Method and Philosophy" and "The History of Blood Transfusion".

## THE RELEASE OF ATOMIC ENERGY

By R. E. Peierls

1. INTRODUCTION. The explosion of atomic bombs, in the trial at Alamogordo, New Mexico, and in earnest over Japan, marks the end of a continuous development that started with the discovery of radioactivity by Becquerel in 1896. Throughout this time the problem held the attention of scientists as one of the most fascinating fields of discovery—but they were more fascinated by what they could learn in this field about the laws of nature than by the prospects of practical applications. It is true that, probably from the very beginning, physicists were aware of the large sources of energy stored in all materials and they all liked to speculate what it would mean if these sources could be tapped, but any practical realisation seemed remote.

In spite of the enormous progress made up to, say, 1938, which was laying the foundations for future development, the situation was then still the same. The study of the atomic core or "nucleus" was by then a well-established and important branch of physics, the splitting of the atom had not only been studied, but could be produced at will in many university laboratories, but there was as yet no indication that it might have practical significance outside such laboratories.

But, by 1940 we find research teams independently in many countries attacking the problem of tapping these new sources of energy, as a terribly practical project, with the hope of success in a short time.

What had happened in the interval was the discovery of the "fission" of uranium by Hahn's experiments and their

interpretation by Meitner and Frisch, and the proof, given shortly after, by Joliot, Halban and Kowarski in Paris and by Fermi and Szilard and their collaborators in America, that in this fission several secondary neutrons are given off.

To the layman these discoveries would have appeared as inconspicuous notes in scientific periodicals stating some numbers obtained in laboratory experiments, yet to any physicist who had ever speculated on the release of atomic energy, these results meant that such speculations were suddenly removed from fantasy to actual possibility.

To be sure, much had to be done, and much had to be learnt, before success was certain, but this moment may be regarded as the turning-point. In the present article we want to explain the arguments that made these discoveries so sensational, and also to outline the work that had to be done from there, which will be covered more fully in the following articles of this series.

2. STATE OF KNOWLEDGE BEFORE DISCOVERY OF FISSION. Later articles will also tell the story of atoms and their structure, but we need a few facts here for our first survey. Atoms are the units of which matter is built. They are extremely small, even the heaviest ones, like uranium atoms, weighing only as much in comparison with a melon as the melon in comparison with the earth. Even though atoms are too small to be visible in the most powerful microscopes, the last sixty years or so have brought many methods of proving their existence, and the article by Frisch will describe examples of ways in which the trace of a single atom can be detected.

It was found that each atom has a central core, or "nucleus", which carries a positive electric charge. This is surrounded by electrons, which are very light particles of a weight about 2000 times smaller than the lightest atom; each electron carries a negative charge.

All ordinary chemical changes in matter are concerned only with the arrangement and movement of the electrons, and usually, in heavy elements, only the outermost electrons, which move with lower speeds and are easier to influence than the inner ones.

The nucleus of the atom comes in only in so far as the amount of electric charge it carries determines the number of electrons necessary to neutralise it; the number of electrons determines the chemical nature of the atom. But in all ordinary chemical or mechanical changes the nucleus of the atom does not change its condition.

This is not surprising because the forces that hold the constituents of the nucleus together are immensely stronger than those that govern the motion of the electrons surrounding it. For example, the energy required to break up the nucleus of a helium atom is about a million times that needed to pry an electron loose from the helium atom.

Accordingly, while energies involved in atomic processes are usually measured in electron volts, those in nuclei can be expressed in million electron volts. An electron volt is the energy which an electron acquires in passing through an electric field under the influence of a potential difference of one volt. Taken absolutely, it is a very small amount of energy, since the charge on an electron is a very small fraction of the electric charges that we are accustomed to deal with. On the other hand, burning a substance such as coal releases about four electron volts *per atom*, and then the energy contained in every quarter pound equals about one kilowatt-hour, the familiar unit of electric power.

It was always evident that if one could succeed in producing a reaction between atomic nuclei one would deal with very much larger amounts of energy.

That some atomic nuclei were capable of undergoing changes which released energy was known ever since the work of Rutherford and others had led to an understanding

of radioactivity. Radioactive elements, i.e., elements that, like radium, continuously emit penetrating radiations, were shown to have nuclei which are unstable and tend to break up, expelling, when they do so, particles of high energy. The particles emitted by such radioactive nuclei are usually positively charged, and they carry away some of the charge on the nucleus, so that the nucleus remains with a smaller charge, and the remaining atom will retain fewer electrons and will be an atom of a chemically different substance.

Hence the process of splitting atoms, and of transmutation of one substance into another is not new but has been going on in nature ever since there was radium, uranium, or any other radioactive element. But there is no way of controlling, of accelerating or stopping this process. It goes on at its own pace and of any quantity of radium, for example, one part in about 580,000 will break up every day, so that after 1600 years only half the original amount is left. If we could hurry nature and make all the radium break up in a few minutes, even small quantities of radium would constitute a respectable source of energy.

Rutherford himself showed later (1919) that the splitting or "disintegration" of nuclei could be produced at will—at a price.

For this purpose Rutherford used as projectiles the particles emitted by radium, or other radioactive elements, which he had called "Alpha-particles" and which turned out to be nuclei of helium, i.e., helium atoms stripped of their electrons, and hence positively charged. These particles are thrown out by the radioactive substance at high speed, the energy carried by each particle being of the order of several M.E.V. (million electron volts). In passing through light elements they would occasionally collide with one of the nuclei, and combine with it, causing the ejection of some other particle, usually a "proton", i.e. a hydrogen nucleus.

Thus the artificial transmutation of elements had been achieved but the amounts were minute and the energy released quite negligibly small. One must here remember that the atom represents a target with an extremely small bull's eye, since the nucleus has an area which is ten million times smaller than that of the rest of the atom. Hence, since one cannot aim the projectiles, only a minute fraction of the shots will, in fact, be hits. Each alpha-particle will, in passing through matter, go through many atoms in turn, and thus have many tries at hitting a nucleus. The number of such tries is, however, limited, since during this passage the particle continuously collides with electrons, thereby gradually losing speed. Now, as its speed is reduced, it finds it increasingly difficult to reach a nucleus, since both the particle and the nucleus are positively charged and like charges repel each other. While a fast particle can overcome this repulsive force fairly easily, this is almost impossible for a slow one, and below a certain speed the particle is practically incapable of reaching the nucleus.

Hence most of the particles must get slowed down and finally stopped without ever making a hit, and only a small fraction, sometimes one in 100,000, sometimes one in a million, are successful. This means that the number of atoms we have split must be at least 100,000 times smaller than the number of radium atoms that broke up to give the alpha particles we used. Therefore, any energy we may be able to recover from the particles which we have knocked off the nuclei we have succeeded in hitting, is many thousand times smaller than that of the alpha-particles we have used, so this method is certainly no way of releasing energy for practical purposes.

From our present point of view the situation was not materially affected by the discovery of Cockcroft and Walton, who showed that instead of the alpha-particles one could use hydrogen or other nuclei accelerated arti-

ficially in an evacuated tube with a voltage of the order of a million volts applied to its end. This made the job easier and speeded up research, but still most of the projectiles stopped before finding a target, and the energy wasted was incomparably greater than that generated.

An important step was, however, the discovery of the neutron by Chadwick in 1932. The neutron is a heavy particle of practically the same weight as a proton, or hydrogen nucleus, but it differs from it by carrying no electric charge. This means that in passage through matter it has no effect on the electrons in its way, and hence it is much harder to detect than charged particles, which are mostly observed by the violent disturbances they cause in atoms along their way. Neutrons do, however, interact strongly with nuclei at close range; they have a strong tendency to attach themselves to nuclei. In fact all nuclei are built of neutrons and protons.

This means that neutrons are much more effective projectiles than charged particles for splitting nuclei, since they are not slowed down in their passage through matter except when they have direct hits on nuclei; moreover, even a slow neutron has a good chance of a direct hit, since it is not kept away from the nucleus by an electric repulsion.

If, therefore, we use neutrons as projectiles, we may hope that in suitable conditions a fair fraction may break up nuclei, instead of only every millionth or so, as with charged particles.

But how are we going to produce neutrons for this purpose? The easiest way to produce neutrons is, for example, to bombard a very light element such as beryllium with alpha-particles from radium. The neutrons from this process were the ones first discovered. We can see that this only moves the difficulty one step further along, since we know already that hitting nuclei with charged particles is necessarily a very wasteful process. While a neutron has

a fair chance of making a hit, we can obtain it only by a process in which we use up much more energy than we can expect to recover from the hit of a neutron on a nucleus.

3. DISCOVERY OF FISSION AND ITS SIGNIFICANCE. This was the state of affairs when fission was discovered. Hahn and his collaborators bombarded uranium with neutrons, in the expectation that neutrons might get lodged in uranium nuclei, thus building up a still heavier nucleus, which might be expected to increase its electric charge by the process known as "Beta-transformation" and thus form new elements beyond the end of the series of elements then known, of which uranium, carrying a charge of 92 units on its nucleus, was the last. We now know that this formation of "transuranic" elements does indeed take place, but in searching for it, Hahn found a completely new phenomenon.

As usual, the amount of new material that is made by such a bombardment is too small to be seen or weighed or handled in any other conventional way. However, such new elements are often radioactive, since, having changed their weight by the capture of a neutron they tend to change their charge also, and this is achieved by a beta-transformation, in which the nucleus gives off an electron (which for our purpose is essentially a charge without weight). Now these fast electrons or Beta rays can be detected by sensitive counters and other methods described in Frisch's article and therefore we can detect such substances in very small amounts. Their chemical nature can be studied by performing a chemical analysis of the sample that had been exposed to the neutrons and seeing which fraction gave the beta rays. For example, if this sample is subject to a chemical process in which barium would precipitate, while other elements remained in solution, we would see whether the solution or the precipitate was an emitter of beta rays. In

the latter case we would say that the radioactive element which we had produced had the chemical properties of barium.

This was indeed found by Hahn, to his surprise, since none of the atoms heavier than uranium should have these chemical properties. More careful analysis showed that there were a great number of radioactive substances with chemical properties similar to many elements of roughly half the atomic weight of uranium.

Lise Meitner and O. R. Frisch then pointed out that this must mean that the neutron had caused the uranium nucleus to undergo fission, or in other words to split into two, roughly equal, parts. It was known already that the heaviest nuclei were of an uneconomical size. They were so highly charged that the electric repulsion of like charges tended to break them up in spite of the binding forces cementing them together. It was known that the energy contained in a uranium nucleus was much more than twice that of a nucleus of half the weight and half the charge. In the ordinary way, such a nucleus holds together since a strong force opposes any effort to break it up. If some work is done to overcome this force (like the effort required to pull the plug out of a full bath-tub against the water-pressure), the further breaking up of the nucleus proceeds by itself and in doing so much more energy is liberated than had to be invested at first.

It was soon verified by many physicists in many places that this explanation was right, since they actually found very heavy particles moving at high speeds, which were, of course, the fragments of uranium nuclei, thrown apart violently as the nuclei split. They carry most of the energy liberated in the process, and this was found to be about 160 million electron volts. To appreciate the significance of this figure, we remember that the energy liberated in burning one atom of coal is 4 electron volts, and that in most radioactive processes is of the order of a few million electron

volts. Here was, then, a much more powerful process than any other known.

Soon after this Joliot, Halban and Kowarski in Paris and two groups in America including Fermi and Szilard showed that in addition to the fission fragments, some neutrons were the result of the process, and that for each uranium nucleus split, several neutrons were obtained. This was the crucial fact, for here was a source of neutrons for which one did not have to waste millions of charged particles in an effort to hit some nuclei.

Supposing, for simplicity, that *all* neutrons hitting uranium nuclei cause fission, and that there are two neutrons given off for each fission. Then if once we have caused one uranium nucleus in a large mass of pure uranium to split, we have two neutrons. Both of these will continue on their path until each hits another uranium nucleus and the splitting of those two nuclei will produce four neutrons altogether. In the next "generation" we shall have eight neutrons, and clearly in this way the number will grow extremely rapidly; after twenty generations we shall have produced about a million neutrons, and only eighty generations are required to create in this way as many neutrons as there are atoms in a sizable piece of uranium metal. Hence, if the process could really be allowed to continue in this way, a staggering amount of energy would have been released in a very short time, since the whole process of using up these eighty generations would take only about eighty times the time that a single neutron needs to find its next victim amongst the uranium atoms.

In this process, which is usually described as a "chain reaction", lies the key to the release of atomic power on a large scale, and from the description it is clear that the two essential features are a reaction which can be caused by a neutron and releases energy, and the emission of secondary neutrons from this reaction.

The picture given here is, of course, over-simplified. It is not essential that we have assumed just two neutrons to be emitted in the reaction, we would equally well get the chain reaction if this number were greater or less than two, provided there was more than one neutron for every neutron used up, so that, as the chain proceeds, the total number of neutrons will grow. It is, however, very important that in reality not every neutron generated in this way will again lead to the splitting of another uranium nucleus.

There are two reasons for this. The first is that sometimes when a neutron hits a uranium nucleus it may get lodged in the nucleus, thus forming one of the trans-uranic elements for which Hahn was looking, and these neutrons are evidently lost from the process since they do not directly produce any offspring. Similarly, any other elements present as impurities in the uranium or as necessary materials of construction may absorb neutrons and thereby reduce the number of secondary neutrons that, on the average, each primary neutron will produce. The second reason is that in practice one always deals with a finite amount of uranium and that the leakage of neutrons from the surface may be appreciable. It has here to be remembered that the "mean free path", i.e., the distance that a neutron can run in uranium, on the average, without hitting any nucleus is quite appreciable. Unless the dimensions of the uranium are rather greater than this mean free path, each neutron will have a fair chance of running out of the material before it could hit a nucleus and produce fission.

We can still use the picture of a chain reaction, only we must not count as significant the number of secondary neutrons produced by the splitting of one uranium atom. Instead we must state what fraction of these will *not* escape through the surface or be absorbed without splitting uranium nuclei, since only these amongst the offspring of

any particular neutron can cause further splitting and thus continue the chain. This number, usually called the "reproduction factor" and denoted by  $k$ , is then vital for the possibility of the chain reaction. If the number is less than one, say if it is 0.99, no chain reaction will form. If, in some way, we have produced 100 neutrons in such a system, the next generation would contain only  $100 \times 0.99 = 99$ . The next after that  $99 \times 0.99$ , which is about 98, etc. On the other hand, if, for example,  $k = 1.01$ , we would from an initial 100 have 101, 102, etc., and after every seventy generations the neutron number would double.

Further investigation of these problems brought the following facts to light. In ordinary uranium the chance of any given neutron causing fission is very small: most of the neutrons will actually be caught and retained by the nucleus. The average distance which a neutron has to travel in ordinary uranium before causing fission, even if it is not absorbed on the way, is very large, and, therefore, even if absorption did not outweigh production very large quantities of uranium would be necessary to produce a chain reaction.

4. CHAIN REACTION WITH SLOW NEUTRONS. An obvious remedy for this last difficulty appeared at once to be the use of very slow neutrons, since it was known that, as in many other cases of collisions with nuclei, both the capture and the fission of uranium happened much more easily at very small velocities. (It might be said with some over-simplification that a fast neutron does not stay near the nucleus long enough to make the latter realise its presence.) It was known that one could easily slow down neutrons if one allowed them to travel through a medium containing very light elements. For example, very suitable slowing-down materials are water or paraffin wax, which both contain hydrogen. The hydrogen atom has about the

same mass as the neutron, and when they collide the result is usually that both move after the collision so that in each collision the neutron will lose about half of its energy. Hence a fairly small amount of water or wax is sufficient to bring the neutron almost to rest. It will ultimately travel at the same speed with which the hydrogen atoms themselves are moving about because of their irregular heat motion.

Attempts were then made to see whether a system made up of uranium and some hydrogen compound such as water could give a chain reaction. Many independent investigations, which were then already carried on in secrecy, were not successful in achieving this. The chief obstacle is that the hydrogen captures some of the neutrons, forming the so-called "heavy hydrogen" which consists of one hydrogen nucleus and one neutron. This, together with the neutrons absorbed by the uranium itself, means a considerable loss, so that the "multiplication factor"  $k$ , may never exceed one.

An improvement first suggested by the group in Paris, and later independently by many other workers in the field, consisted in arranging the materials in layers or in some other regular pattern, keeping the uranium separate from the slowing-down substance. The point here was that uranium is particularly liable to capture neutrons at intermediate velocities, which the neutrons would reach in the course of being slowed down. By mixing the materials less intimately one could ensure that neutrons had less chance of meeting a uranium atom while they were in the process of slowing down to the final velocities. This gave some improvement, but still no success in establishing a chain reaction.

The work then turned to other substances in place of hydrogen which were not as light and, therefore, were not as efficient in reducing the speed of the neutrons, but which in proportion absorbed even fewer of the neutrons.

Attempts were made to use for this purpose pure carbon in the form of graphite or heavy water, i.e., water in which the hydrogen is replaced by "heavy hydrogen". We now know that both methods are possible, but both are extremely difficult. In the case of the graphite system, the difficulty is that even in ideal conditions the multiplication factor  $k$  is only barely greater than one, and any impurity in the graphite or in the uranium is liable to introduce sufficient absorption to reduce it below one and make the whole system unworkable. For the same reason the loss of even a small fraction of the neutrons through the surface would be serious. One, therefore, has to make the system very large so that the numbers escaping through the surface should represent only a small fraction of the number of neutrons present in the system.

In the other case, the chief difficulty is the supply of heavy water, which has to be separated from ordinary water in which it is present only as an extremely small trace, so that the methods of isolating it are laborious and expensive. The scheme involving graphite was the one actually adopted for the American project, and more details about it can be found in another article of this series.

5. THE ROLE OF U-235. EXPLOSION. In the meantime, there was a parallel development based on the following consideration. From the observations on the process of fission, Bohr had concluded that, for the capture of neutrons and for fission by slow neutrons, two different kinds of uranium were responsible. It is known that uranium atoms are of different kinds, distinguished chiefly by their weight, the most common one being the heaviest with a weight of 238 units, the rarer one, of which there is only one to every 140 of the heaviest, having a weight of 235 units. More about these "isotopes" can be found in the article on "Isotope Separation". Bohr concluded then that

only the rather light isotope, uranium 235, could be split by slow neutrons, whereas most of the capture of neutrons was due to the heavy one. It was immediately clear that it would be very much easier to release atomic energy if one could obtain a quantity of the rare isotope uranium 235 separated from the other; but it was well known that to separate the isotope of so heavy an element was a job that went far beyond the wildest dreams of anybody thinking about laboratory experiments; no-one seemed prepared to take such a suggestion seriously.

This situation changed, however, when people started to think out in earnest what one could do with separated uranium. This consideration must have occurred to many people. It is natural for the present writer to think of the discussions of Frisch and Peierls at Birmingham, in which they tried to guess, following Bohr's ideas, the properties of uranium 235. As explained before, a slow neutron had an appreciable chance of causing fission in ordinary uranium, and this chance, according to Bohr, was entirely due to the uranium 235 contained in ordinary uranium. Separated uranium 235 would obviously give the neutron a much better chance, and, at the same time would eliminate almost entirely the chance of capture. In other words, almost every one of the neutrons would be able to split a uranium atom, and as long as the number of neutrons resulting from this was well above one, the success of the chain reaction was practically assured. If the neutrons are not slowed down they have to travel somewhat further before they make a collision, but since they will split the uranium in a good fraction of the collisions they make this will still only mean that one has to employ an amount whose dimensions are not greatly in excess of the "mean free path". Moreover, if we are using pure uranium 235, the rate at which the chain builds up is very much greater than with the other process described before. In both cases the

neutrons have not been slowed down and, therefore, are still moving with high velocity, and waste less time between collisions and also, because the multiplication factor may now be well above one, fewer generations are required to reach any definite multiplication.

This distinction is important because, if we would let the reaction with slow neutrons go on without stopping it, it would take enough time to allow the material of our system to be molten and eventually vaporised as a result of the high temperatures caused by the energy we are setting free, and as the system expands it will occupy greater space, thereby increasing the chance of neutrons finding their way out without making collisions, and quite soon the multiplication rate will have dropped below the critical value of one. This will, in fact, happen when not much more energy has been liberated than is necessary to vaporise the uranium and whatever goes with it, so that an explosion caused in this way, while very powerful, will release only a very small part of the energy contained in the uranium. If, on the other hand, we could cause a reaction with fast neutrons in a system with a multiplication factor well above one, the time in which the reaction is complete is so short that even if the material is completely vaporised it has not time to move very far before a substantial part of the reaction is complete. Actually, the fraction of the available energy that can be liberated by an explosion of this kind depends a good deal on the arrangement of the material and, the container that surrounds it, and a discussion of some of these factors will be found in the article on "The Physics of the Bomb".

But even the crudest estimate of the power of such an explosion made it clear that its military value would justify an extreme effort in attempting the separation of the uranium isotopes and that this should be tackled, not from the point of view of laboratory experiments, but from the point of view of an industrial process. The question of what

is involved in this is discussed in the article on "Isotope Separation".

6. **PLUTONIUM.** About the same time, another line of approach was found to the same end. We have previously seen that one could produce a chain reaction with slow neutrons, but that of these neutrons a fraction will not cause fission but will be captured by the uranium. Whenever this happens the uranium nucleus of weight 238 will be turned into a new isotope of weight 239 by the addition of the neutron. It turns out that this new nucleus, for greater stability, needs a higher charge, and it therefore proceeds by the process known as beta-transformation to emit in succession two electrons, each carrying one unit of electrical charge and very little mass. Thereby the nucleus becomes, instead of a uranium nucleus with charge 92, the nucleus of charge 93 called neptunium and then 94 or plutonium. This new element, plutonium, was discovered at Berkeley in 1940. From the laws of the behaviour of heavy nuclei, one had to expect that plutonium would have very similar properties to the light isotope of uranium and it was, therefore, likely that it would be equally suitable for use in a military weapon. At first very small amounts of this element were produced in the laboratory, essentially by the wasteful methods outlined in the beginning of this article and with these it was possible to confirm that plutonium, like uranium 235, had a strong tendency to split when hit by a neutron.

This leads to a scheme that might, at first sight, sound more fantastic even than a large-scale separation of isotopes: a slow neutron reaction is allowed to proceed in a controlled way, so as not to destroy the plant; in this system some neutrons cause fission in uranium 235, thereby producing the new neutrons needed to continue the reaction, and also producing energy which has to be disposed of and

could, in principle be utilised. Other neutrons will convert some of the uranium into the new element plutonium. This has somewhat different chemical properties from uranium and when enough of it has been accumulated one can extract it from the uranium by ordinary chemical methods. The plutonium obtained in this way is the second of the powerful atomic fuels known, and it is well known by now that, while one of the two atomic bombs dropped on Japan was made of uranium 235, the other contained plutonium.

7. **POWER PRODUCTION.** As the field of atomic energy is further explored, its application to peaceful purposes must gain in importance, as compared to its use for destruction and here both processes, the production of energy from ordinary uranium in a large system or "pile" and the chain reaction in much smaller amounts of separated uranium 235, or of plutonium, may be of vital importance. The reaction with ordinary uranium is clearly the more attractive one economically, but it involves a very large plant, whereas the use of the very expensive fuels uranium 235 and plutonium results in a very much more compact power unit, which, for a long time to come, will be the only one worth serious consideration for mobile power. Even so, the need for protecting personnel from the intense radioactive radiation given out as a by-product of any system liberating atomic power, means that one has to use heavy shields of concrete or similar material to surround the unit, and for this reason the use of atomic power for cars and locomotives would, for the present, seem to belong entirely to the realm of speculation. The same could not be said about using power in ships and units of similar size, but even for these there are many technical problems yet to be solved, and many economic factors to be thought out, before we know what advantages can be obtained from such an application.

One use, however, can almost immediately be made of the new possibilities. This is the utilisation of the new radioactive elements, whose presence in the power production appears merely as a great complication and inconvenience. Some possible uses of these materials are discussed in the article on "Tracer Elements".

## ATOMS AND NUCLEI

By H. A. Bethe

ALREADY the ancient Greeks knew the concept of the atom. They argued that if you take a piece of matter of any kind and divide it again and again into smaller parts you finally come to an end, to parts so small that they can no longer be divided by any means. These they called atoms, which means indivisible things. Of course the idea that matter consisted of atoms was not universally held; many Greek philosophers believed that subdivision *could* be continued indefinitely and that there were no atoms. Neither side had any evidence in favour of its beliefs and it was only in modern chemistry and physics that the atomic hypothesis got a solid foundation.

Modern chemistry began with the researches of the French chemist Lavoisier and his contemporaries at the end of the 18th century. They showed that most of the common substances can be decomposed by chemical action into simpler substances which they called chemical elements. Since then 88 different chemical elements have been found in nature. They include hydrogen and oxygen, the two elements contained in water; nitrogen, which with oxygen forms the main part of air; carbon, one of the fundamental elements in the human body and other organic matter, and many others. Metals like iron, copper, gold, mercury are chemical elements.

If a piece of an element, let us say a piece of iron, is divided into small parts and this division is continued, one finally arrives at small indivisible units which are the atoms of modern chemistry. If a piece of an ordinary chemical substance, a "chemical compound", is subdivided

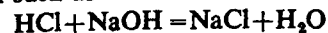
in the same way and not subjected to chemical action, we finally arrive at the smallest unit which still has the properties of the compound and which is called a *molecule*. All facts of chemistry can be explained by assuming that the molecule of any given substance is composed of a definite number of atoms of various kinds. The number of atoms in a molecule is usually quite small; for instance the water molecule contains 2 atoms of hydrogen and 1 atom of oxygen, which is indicated by its chemical formula,  $H_2O$ . A molecule of ordinary table salt contains 1 atom of sodium and 1 atom of chlorine,  $NaCl$ . Only if we go to the more complicated organic molecules do we have many atoms in one single molecule.

Chemistry was able to show that the atom of each chemical element has a definite weight called the *atomic weight*, and to determine this *atomic weight*. For instance, when water is decomposed into its elements, it is found that in every case 16 grams of oxygen are formed for each 2 grams of hydrogen. With the chemical formula  $H_2O$ , this means that one atom of oxygen must weigh 16 times as much as one atom of hydrogen. It was found in this way that hydrogen had the smallest atomic weight, and this atomic weight was therefore used as a unit. The atomic weights of the elements range from 1 for hydrogen to 238 for the heaviest atom, uranium.

It was just the fact that decomposition of each chemical compound always led to the same proportions of the chemical elements that gave support to the atomic hypothesis. No matter how small an amount of water is decomposed, the ratio of hydrogen and oxygen is always the same; therefore dividing a water drop into smaller droplets does not change its chemical composition. It is a most natural assumption that this composition is determined by the fact that the smallest units of the elements, the atoms, combine in some simple way to form the molecules,

the smallest units of the chemical compound. It required very long study to determine the number of atoms of each kind in a given chemical molecule; to show, for instance, that water contains two hydrogen atoms for each oxygen atom rather than equal numbers of each. This study was helped by the integration of many different facts of chemistry and physics.

In chemical reactions the molecules change their composition but the atoms always remain the same. In a simple reaction such as



the properties of the end products of the reaction, salt and water, are completely different from those of the initial substances, hydrochloric acid and caustic soda. However, the number of atoms of each kind is preserved; we have in the beginning two atoms of hydrogen, and one each of oxygen, sodium, and chlorine, and we have exactly the same atoms in the end.

Chemistry had thus answered the problem of the alchemists. The alchemists' aim was the change of cheap metals like lead or iron into expensive ones like gold. Chemistry stated that this was not possible; each of these metals was an element and it was not possible to change the number of atoms of each element.

Two remarkable discoveries were made when the atomic weights of the various elements became accurately known. The first of these was the periodic system of the elements which was discovered by Mendeleev. He found that if you order the elements according to increasing atomic weight, then their chemical properties will repeat periodically. For instance, some elements are known as alkali metals: they include the common elements sodium and potassium. The element following an alkali metal in atomic weight will invariably be an "alkaline earth" like magnesium and calcium while the element preceding an alkali

metal is always a noble gas like helium, neon and argon.

The second fact was that most atomic weights turned out to be near integers; this rule was even more accurately fulfilled when the atomic weight of oxygen was taken to be exactly 16, rather than that of hydrogen exactly equal to 1. With the weight of oxygen 16, the weight of hydrogen turned out to be 1.008, sufficiently close to 1. There were some notable exceptions to the rule, such as chlorine which has an atomic weight of 35.5, but the rule was sufficiently generally fulfilled to draw the attention of chemists.

Toward the end of the 19th century it became possible to determine the number of atoms in a given mass of material, or the weight of an individual atom. This was made possible by the kinetic theory of gases which explains for instance the pressure of air by the motion of the molecules of the air. The best measurements made since then show that for instance an ounce of water contains about a billion billion\* molecules. This is an enormous number; so the size of one individual atom is exceedingly small. About one hundred million atoms laid side by side are an inch long.

The atom of 19th-century chemistry was like the atom of the ancients, indivisible and unchangeable. The first sign of its divisibility came at the end of the century, when the English physicist Sir. J. J. Thomson described how small electric particles can under certain conditions come out of atoms. These small particles he called *electrons*; they were all found to be alike in charge as well as in weight. The charge of the electron is negative and is the smallest electric charge that has ever been observed. It is therefore used in physics as a unit of charge. The weight of an electron is much smaller than that of the lightest

\*A billion is used here according to the English usage, meaning a million million. In American usage this number is called a trillion.

atom; about 1840 electrons weigh as much as one hydrogen atom.

If there are negative charges in the atom there must also be positive charges because the atom as a whole is electrically neutral. In 1910 Lord Rutherford discovered the details about the positive charge. He found that the positive charge of each atom was concentrated in a very small space and was intimately connected with the largest part of the weight of the atom. This large mass carrying the positive charge he called the *atomic nucleus*, and thus was established the present picture of the atom: a massive nucleus, positively charged, surrounded by a number of negatively charged electrons.

The size of the atomic nucleus is exceedingly small. The diameter of the atom is about 20,000 times greater than that of the nucleus. The size of the electron has not been satisfactorily determined but is certainly not greater than that of the nucleus. Therefore the atom consists mostly of empty space, and if you could fly through atoms you would only occasionally meet either an electron or a nucleus.

The weight of the atom is the sum of the weights of the nucleus and of the electrons, and since the electrons weigh practically nothing, the weight of the nucleus is almost the total weight of the atom. The electric charge of the nucleus which is positive must just compensate that of the electrons around it. We know that all electrons have the same charge, which we may call  $-e$ , we therefore find that the charge of any nucleus must be a multiple of the unit positive charge  $+e$ . How many units of positive charge a given nucleus contains can be determined by experiment, the most accurate way being the wave-length of the characteristic X-rays which are emitted by the atom. In this way it is found that the hydrogen nucleus has just 1 unit of charge, the next heavier nucleus, helium, 2 units; carbon,

nitrogen, and oxygen have respectively 6, 7, and 8 units of charge, and the heaviest nucleus, uranium, has 92 units. It turns out that the *nuclear charge* increases from element to element together with the atomic weight. Each element has its characteristic nuclear charge, and one can number the elements conveniently by the number of units of charge carried by their nucleus.

We have mentioned above that 88 chemical elements have been found in nature. This is slightly less than the 92 for which there would be room according to the different possible values of the nuclear charge. The remaining four elements, of charge numbers 43, 61, 85, and 87 do not occur in nature because their nuclei are unstable. Discovery of some of these has been claimed repeatedly but these claims were always found to be false. The elements can, however, be produced by nuclear transformation as we shall see later, and their properties have been investigated.

A nucleus which has  $Z$  units of positive charge will assemble around itself  $Z$  electrons in order to form a neutral atom. If by some chance the atom should have lost one or several of its electrons it will eagerly attract other electrons which may happen to be in its surroundings, and will recombine with these electrons to form a neutral atom again. This is due to the strong electric attraction between the negative charge of the electron and the positive charge of the remaining atom.

In 1914 the great Danish physicist Niels Bohr developed a complete theory of the atom on the basis of Rutherford's ideas and of the quantum theory. He showed how to calculate the motion of the electrons and how to find from this motion the properties of the atoms. In its present form, this theory is believed to give a complete description of the properties of the atoms. It permits one to calculate the wave-length of the spectral lines which the atoms emit,

and to predict their chemical properties. The theoretical predictions are sometimes difficult to make because of the very complicated mathematics involved; but whenever the calculations have been performed, their result was found to agree with experiment to an amazing precision, which may be as good as 1 part in a million.

The properties of the atom can be predicted merely from the knowledge of the number of electrons in the atom. It is therefore this number of electrons which determines the chemical behaviour; it determines for instance that 2 atoms of hydrogen will combine with 1 atom of oxygen to form a water molecule. The number of electrons in turn is determined by the nuclear charge, so it is ultimately the nuclear charge which determines the properties of a chemical element. On the basis of Bohr's theory of atomic structure it was possible to explain in detail the periodic system of the elements discovered by Mendeleyev.

The electrons of an atom can be removed without very great difficulty, for instance in an electric spark. This process also goes on in very hot gases, for instance in stars, and also in the cathode of a radio valve in which the electrons are separated from the atoms of the cathode. The removal of electrons requires considerable energy because of the electric attraction between the electron and the positively charged remainder of the atom; it is therefore not a source of energy. It might properly be called atom splitting, but it is not given this name in common usage.

The atom of Rutherford and Bohr is divisible and has a structure. However, the nucleus of this atom might still have been indivisible. This assumption, however, turned out to be false. Even before Rutherford's discovery, and in fact forming an important tool in that discovery, it had been found that some of the heaviest atoms emit strange radiations called *radioactivity*. These radiations come from the atomic nucleus. The uranium nucleus and the nucleus of

the well-known element radium are examples. Both of these emit particles which carry two positive charges and can be shown to be identical with the nuclei of helium. By emitting these particles, which are known as alpha particles, the element radium, which is a solid metal, turns into a gas called radium emanation. The charge of the nucleus of emanation is two units less than that of the radium nucleus, just the two units which were taken away by the alpha particle. The helium atom has an atomic weight of 4 units, and it turned out that the nucleus of emanation had an atomic weight 4 units less than that of radium.

Other radiations also came out of the radioactive nuclei, so-called beta rays. These are ordinary electrons carrying one negative charge and practically no mass. Accordingly the nucleus after emitting them had gained one unit of positive charge and had not changed its atomic weight.

When first discovered, the phenomena of radioactivity seemed restricted to the very heaviest nuclei, namely those carrying a charge of 82 units or more. Moreover, the splitting of these nuclei occurred spontaneously, without any external influence and independently of such influences. It is known as natural radioactivity or as spontaneous radioactive decay. A completely new perspective was opened in 1919 when Lord Rutherford used alpha particles to bombard the nuclei of nitrogen. He found that occasionally a completely new particle resulted from such a collision which turned out to be a hydrogen nucleus, a so-called proton. The nitrogen nucleus itself was transformed in this process into a nucleus of oxygen.

By this discovery the concepts of classical chemistry were profoundly changed—although, of course, the *practical* conclusions of chemistry were unaffected. It was now possible to *change one chemical element into another by bombarding its nucleus*. Not only the atom but even the

nucleus had been shown to be divisible and to contain yet smaller particles.

What these particles were was only revealed in 1932 when Sir James Chadwick discovered still another type of particle coming out of light nuclei bombarded by alpha particles. These new particles had no electric charge, they were electrically neutral and were therefore called neutrons. They had very nearly the same weight as protons, the nuclei of hydrogen.

It is now well established that the fundamental units of an atomic nucleus are neutrons and protons. The number of units of *charge* in the nucleus is equal to the number of protons contained in the nucleus, each proton contributing one unit of positive charge. The atomic *weight* is approximately equal to the sum of the numbers of neutrons and protons.

Considerably before the discovery of the neutron it had already been found that there were several species of nuclei of the same element. These species are called isotopes. All isotopes of one element have nuclei of the same nuclear charge, because it is the nuclear charge which determines the chemical properties of an element. The isotopes differ, however, in their atomic weight. According to our present ideas, then, all isotopes have the same number of protons in the nucleus but the number of neutrons is different for different isotopes.

The discovery of isotopes gave the explanation why certain chemical elements have atomic weights which are not integers. For instance the element chlorine was found to consist of two isotopes of atomic weights 35 and 37, present in the ratio of about 3 to 1 in natural chlorine. This makes the atomic weight of natural chlorine 35.5.

Almost every chemical element was found to consist of several isotopes. Even hydrogen has two isotopes, one of weight 1 and one of atomic weight 2. However, the

latter, called heavy hydrogen or deuterium, is present only in minute amounts, namely only about 1 part in 5,000 of natural hydrogen. Some elements have very many isotopes, for instance tin has 10. When the weights of the individual isotopes were determined they were found to be much closer to integers than the ordinary chemical atomic weights had been, but even they were not exactly integers.

We have said before that nuclei consist of protons and neutrons. These neutrons and protons, or nuclear particles, are held together in the nucleus by the strongest forces known. The forces are about a million times stronger than the electric forces that hold the electrons in the atom. These forces are stronger than the chemical forces which hold together the atoms in a molecule. The chemical forces again are many times stronger than the elastic forces which hold together, for instance, a piece of steel—and everybody knows how difficult it is to tear apart a piece of steel.

There is a very convenient method of measuring the strength of the nuclear forces. This is based on Einstein's theory of the equivalence of mass and energy. This theory, which is a part of the well established special theory of relativity, states that one gram of mass is equivalent to an enormous amount of energy, namely about 25 million kilowatt-hours. This is the output of a very large electric power plant such as that at Boulder Dam for one day.

The application of Einstein's theory to nuclei is connected with the fact that the atomic weights are not exactly integers. More precisely, a nucleus of oxygen which contains eight protons and eight neutrons, weighs nearly 1% less than the separate protons and neutrons would weigh. According to Einstein's relation, this means that the oxygen nucleus contains less energy than the separate protons and neutrons, and in fact very much less energy, because the energy equivalent of even a small amount of mass is so large.

Since the oxygen nucleus contains less energy, energy would be required to tear it apart into its protons and neutrons. The splitting of the oxygen nucleus into protons and neutrons would therefore not be a source of atomic energy, but would on the contrary require large amounts of energy to accomplish. The difference in atomic weight between a nucleus and the separate protons and neutrons of which it is made is a measure of the great strength of the nuclear forces.

All existing nuclei have this property of having less weight than the separate protons and neutrons of which they are made. Therefore in all nuclei neutrons and protons are bound together with strong binding forces. Very little is known about these forces except their great magnitude, and it is one of the most important and interesting problems of physics to explore the nature of the nuclear forces. It is sure that they are not electric in nature because electric forces are much smaller; and even less can they be explained as gravitational forces, which are smaller than nuclear forces by a factor of many billions of billions. Many theories have been made about the nature of the nuclear forces, but none of them so far has explained all known facts.

Energy is set free when protons and neutrons are brought together to form more complex nuclei. This is the principle by which the stars are supposed to generate their energy. In the stars, in effect, two protons and two neutrons are combined to form a nucleus of helium, a process which is connected with a great release of energy. This combination cannot take place directly, but only by means of a complicated sequence of reactions in which carbon and nitrogen nuclei serve as catalysts. These reactions go on in billions of atomic nuclei every second in the sun.

Energy can, at least in principle, also be released by the splitting of nuclei. Whereas all nuclei are lighter than the sum of the neutrons and protons of which they are made,

reaction was small (a neutron, a proton or a nucleus of heavy hydrogen or helium, having an atomic weight of at most 4), but also one of the particles resulting from the reaction was always small, again having an atomic weight of 4 or less. All the remainder of the nuclear particles remained in the other nucleus resulting from the reaction.

For the first time in 1938 this picture was changed. A nucleus of uranium was split into two almost equal parts. This was shown for the first time by the German chemist Otto Hahn who received the Nobel prize for 1945 for this discovery. Subsequent scientific development was very rapid, and it was shown that the uranium nucleus can be split up in many different ways, but in each case so that the weights of the two fragments were approximately equal.

As soon as this phenomenon, the nuclear fission, was discovered, physicists were able to calculate the energy release for this process by means of Einstein's theory. The nucleus of uranium is about 0.1% heavier than that of the sum of the two fragments into which it can break up, and we have seen that this corresponds to a very great energy. This energy was measured independently by direct experiment and Einstein's relation was confirmed. Confirmation of this relation had previously been obtained in very many instances by the observation of ordinary nuclear transformations.

From the scientific point of view, the remarkable thing about nuclear fission was the splitting of a nucleus into two almost equal parts. From the practical point of view, however, the most interesting feature of fission is that this process is produced by bombarding a uranium nucleus with neutrons, and that in the process itself neutrons are again emitted. On the average the number of neutrons emitted in each fission is greater than 1; therefore the process gives the basis for a nuclear chain reaction.

If we take a large block of uranium 235, which is the

isotope undergoing fission when bombarded by slow neutrons, the following events can happen. A neutron emitted by some source falls on one uranium nucleus and causes fission in it. Let us assume that two neutrons are emitted in this process. Let us further assume that the block of uranium is large enough for none of these neutrons to be able to escape, and also that no other process can be induced by neutrons in U235. Then each of these two neutrons will again cause fission. In each of these fissions again two neutrons will be emitted, and the resulting four neutrons will again cause fission. This process will go on, always increasing the number of neutrons available. In each fission a large amount of energy is set free from the uranium nucleus. The process will finally stop in one of three ways, either (a) by some external control such as is being used in the neutron "piles" described in another article in this book or (b) because the large amount of energy developed will cause a high pressure and thereby an explosion of the uranium—this is the basis of the atomic bomb—or (c) simply by the consumption of all the available U235 on which naturally the process must stop.

In other articles in this book the application of the fission process both to a controlled reaction and to the construction of an atomic bomb is described. In the controlled fission reaction we have a very flexible, intense and cheap source of neutrons, many thousand times more powerful than the largest cyclotron. The properties of neutrons can be studied with much greater ease and precision than was possible before the discovery of fission and of the uranium chain reaction. Moreover, these neutrons can be used to produce in quantity new species of atomic nuclei, especially radioactive nuclei emitting beta rays. These nuclei are useful for biological, medical, chemical and industrial research. Finally the controlled nuclear chain reaction can be used to transform the uranium itself into plutonium, an element

just sufficient to neutralize that charge, so that a hydrogen nucleus and an electron together form an atom which has no net charge, and therefore no strong tendency to attract other electrons. In sodium, on the other hand, the charge on the nucleus equals that of eleven electrons, except that it is positive, so that eleven electrons are required to neutralize it. The charge on the nucleus is also called the "atomic number". The atomic number of hydrogen is 1, that of sodium is 11. This number determines the chemical behaviour of the element, since all chemical changes are changes in the arrangement and motion of the electrons in the outer parts of the atom. Any small core carrying a positive electric charge equal in amount to that of eleven electrons will gather eleven electrons so as to neutralize its charge, and the whole will then behave in every respect like an atom of sodium, no matter what the weight or the structure of the core.

We can now see that a sodium nucleus cannot simply consist of protons (or hydrogen nuclei) since its weight equals that of twenty-three protons, whereas its charge equals that of only eleven protons.

The explanation became clear when Chadwick discovered the neutron, which weighs about the same as a proton, but has no charge. It was then evident that the sodium nucleus consisted of eleven protons and twelve neutrons.

At the same time this discovery explained the existence of "isotopes". It had been noticed that by no means all elements obeyed the rule that their atomic weight was nearly a multiple of that of hydrogen, and this, together with facts found in the relations amongst radioactive elements, had led Soddy to the idea that not all atoms of an element might be alike, but that some of them might have weights different from others, although their chemical nature was the same. Such atoms are called "isotopes".

From what we said before, this would clearly happen if

there were nuclei that had different weights, but the same amount of electric charge; they would both be surrounded by the same number of electrons moving in exactly the same way, and they would undergo precisely the same chemical reactions with other elements. Since the nuclei consist of neutrons and protons, it is then clear that isotopes of the same element each contain the same number of protons (and hence have the same electric charge) but different numbers of neutrons.

The existence of such isotopes was definitely proved by means of the mass spectrograph, an instrument perfected by Aston. Its principle is roughly this: In an ordinary gas the atoms or molecules move in a very irregular fashion, since they collide with each other. If we reduce the amount of gas in a tube, however, by pumping some of it out, the remaining atoms will meet fewer atoms on their way with which they could collide, and they will therefore go in a straight line for longer stretches. It is possible to evacuate a tube to such a high degree that the remaining atoms will hardly ever collide with each other and that each atom has a good chance of travelling the whole length of the tube without disturbance.

If we now pass an electric discharge through such a gas (such as is used, for example, in the familiar tubes of neon signs, except that these are not as highly evacuated) some atoms will collide so violently with each other, or with stray electrons, as to have one or more electrons knocked off in the process. After this they are electrically charged, since the number of their electrons no longer equals that of the positive charges in the nucleus. Such charged atoms are usually called "ions". If the tube contains metal plates which are electrically charged, the ions will now be attracted or repelled by the plates; they will no longer move in straight lines, but go along a curved path inclined towards the plate carrying a negative charge.

Now compare two ions of different weights, each having lost one electron and therefore having the same positive charge. Let us further assume that both move with the same speed. Then the force due to the charged plates will pull on them to the same degree, but the heavier one, owing to its greater inertia, will respond less to this force and will, therefore, be deflected less from its straight path. The situation is the same as when we throw a wooden and a paper ball of the same size against a strong wind. The force of the wind on each of them is the same, but it has much more effect on the lighter one; the heavy one keeps going because of its greater inertia.

Hence, if we have arranged in the tube slits which make sure that all ions initially travel along the same straight line, we shall find them at the other end grouped according to mass, the heavy ones being closer to the straight path.

In actual practice the problem is more difficult because there is no simple way of making all ions start with the same speed. A faster moving ion will be deflected less than a slow one, and this would confuse the distinction between a heavier and lighter ones. In order to overcome this difficulty, the actual mass spectrograph does not use merely the field of electrically charged plates to deflect the ions but, at the same time, provides a magnet outside the tube. This produces a magnetic field which also tends to deflect the ions, since a moving electric charge behaves like an electric current and is deflected by a magnetic field in the same way as the armature of an electric motor is set moving in the magnetic field of the motor.

The magnetic deflection depends on the speed. If, therefore, we arrange the tube in such a way that the deflection due to the electric plates is in a horizontal direction, that due to the magnetic field in a vertical direction, then, if we catch an ion in the far end of the tube its horizontal and vertical deviation from the straight line tells us both

its mass and its speed. In fact, the ions can be detected if a photographic plate is placed at the end of the tube. By running the tube for a sufficiently long time many ions will have reached the plate and will have blackened it at the points corresponding to certain masses, and by measuring the blackening some estimate can be obtained of the number of ions of each particular mass. There are other more sensitive ways of recording the arrival of the ions in each position, but we need not describe them here (plates 7, 9).

By means of this instrument,\* Aston succeeded in showing that for most elements there existed, in fact, isotopes of several different masses. The mass of each isotope was nearly equal to a multiple of the hydrogen atom. Actually the masses were always found to be slightly less than a multiple of the hydrogen mass. But we shall not enter here into the explanation of this "mass defect".

The element uranium, with which we are here concerned, was in this way found to consist mostly of atoms of weight 238, but a weak isotope of weight 235 was found, of which there is approximately one atom for every 140 uranium atoms, and a third isotope of weight 234 is even 100 times less frequent than 235. The isotope 235 is of particular value as an atomic fuel, as has been explained in the first article. The problem, therefore, arises of separating this isotope from ordinary uranium.

**2. THE PROBLEM.** One is faced with the question, then, how to separate uranium 235. In order to understand what this implies, the following illustration may help. Imagine one had a warehouse filled with tennis balls, all of the same size. A small portion of these, less than one per cent, are a little lighter than the rest, their weights being roughly in the ratio of 99 to 100. We are given the task of sorting out

\*The actual arrangement used by Aston differs from the one here described but it was based on similar principles.

the lighter balls. The natural means of doing this, in the case of tennis balls, would be to weigh each ball on scales and sort out the ones of lower weight. But this necessarily involves handling each ball separately, and therefore is a procedure that cannot be adopted in the case of atoms. The next best thing would be to follow the method that is usually applied to separate grain from chaff—by throwing a continuous stream against the wind in conditions where the air resistance matters. The lighter objects for which the air resistance has a larger effect will land in a different place. If we want to apply this procedure to tennis balls, it is clear that we have to devise a very accurate gadget for throwing them, since we cannot expect more than one per cent difference in the distance they will cover, and also since there are so many more of the heavier ones that any slight error in aiming would make the heavier ones cover a wide range and completely swamp the place where the light ones should collect. Apart from the need for extreme precision this plan is quite feasible and, in fact, is one of the methods actually employed for the separation of uranium isotopes. If we consider the mass spectrograph described in the first section of this article, it is clear that it is, in principle, a device for separating isotopes along just such lines. However, as employed, for example, by Aston it is capable of handling only very small amounts of material. It had been regarded as a great achievement when Oliphant and his collaborators managed to obtain by means of a mass spectrograph quantities of isotopes that would not merely make impressions on a photographic plate, but that could actually be studied in their physical behaviour by the effects produced when strong beams of fast particles collided with them. Even so, these samples that it had taken a long time to collect were too small to be weighed; the quantities now required would be many pounds, that is to say some thousand million times more than the greatest amount pro-

duced by a laboratory mass spectrograph. It is clear that, in order to get anywhere, one would have to construct a plant that would look very different indeed from an ordinary mass spectrograph, even though employing the same principle.

This is, however, not the only way in which one might proceed. The alternative is, to return to our picture of tennis balls, sorting them by dividing the whole amount first in two parts by some device which would give some slight preference to the lighter ones. For example, we might put a large number of such balls into a box and shake the box for a long time. In this way, more light ones would be found near the top of the box than near the bottom, but it would not be practicable to go on until all the light ones had risen to the top because, by continued shaking, we would always mix up the balls again to some extent. We might, however, now take out the balls in the upper half of the box and proceed to shake those again. In the new smaller box there would be more light ones at the top than near the bottom. By repeating this process again and again we could eventually reach a point where we had only light balls left near the top. At first sight, one would think that the best procedure might be just to take the upper half, in which case starting with 10,000 balls we would take the upper 5,000 out of the first box, shake these again and use the upper 2,500. Repeating the same procedure we would be left with 1,250 and so on. Clearly, if we go on in this way, we reduce very rapidly the amount of material we are handling and we would in this way recover only a small fraction of all the light balls we set out to find. This procedure, while possible in principle, is too wasteful in practice. To make it work we have to modify it by a trick well known to chemists who separate materials by distillation or other means, and that is by using the "cascade" principle.

By this we mean the following: Start again with 10,000

balls, shake them in the box and take out the upper 5,000. However, we do not discard the lower 5,000 which contain fewer light balls than the original mixture. Instead we also shake the lower half in a separate box. When this is done, the upper half of this box now contains more light balls than when we started and, in fact, contains about as big a fraction of light balls as in the original mixture. These we can, therefore, return to the starting point and carry them along with the next fresh supply. The lower half of this

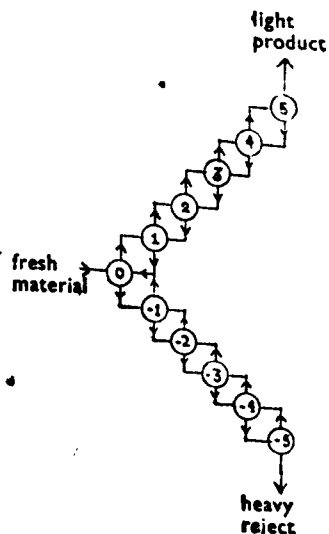


FIG. 1.

last box now contains even fewer light balls. It will be split again and the upper part will be brought to a point where it is the same mixture as the lower 5,000 from the first separation. It can, therefore, be included when we again get a lower batch of 5,000 from a fresh supply once treated.

The principle of this method now becomes clear, and the scheme of such a "cascade" is illustrated in fig. 1. Here each

circle represents a "stage", such as our process of shaking a box; the material used in the process is, for convenience of drawing, shown as entering from left and right. The "light fraction" which is in our example the contents of the upper half of the box, after shaking, is shown to come out at the top, the "heavy fraction" at the bottom.

The stages are numbered, 0 being the one handling fresh material; in stages 1, 2, etc., the material contains successively more of the light component, in those numbered -1, -2, -3, the material gets successively heavier.

Each stage is fed with the light fraction from the previous stage, and the heavy fraction from the succeeding stage, and these have just the same composition. For example, starting at stage 0, which contains natural material, the light fraction transmitted to stage 1 is somewhat richer in the light component, and therefore the material processed in stage 2 is somewhat richer than the natural mixture. The heavy fraction returned from stage 2 is, however, depleted by just the same amount by which the light fraction is enriched, and is therefore just back to the natural composition. The same is evidently true for any other stage. The diagram shows five stages above, and five below, the normal composition, but the scheme can be extended to as many stages as required. From the highest stage a product of the required concentration is obtained, the lowest stage discharges material which is depleted in the light component, and which, if necessary, can be made to consist only of the unwanted heavy component.

It is also clear that the amount of work to be done in going through this process may be very large, because in the stages in which the fresh supplies are first handled, we must handle, in addition, the amounts returned from other stages for retreatment, and if we were dealing, for example, with 100 stages in the process the amount that would have to be handled in the first stage might be about 100 times the

original supply, since each ball on the average may be handed back 100 times for reprocessing before it finally finds its way to one of the end stages.

The cascade principle which we have described here has to be used whenever we work a process that does not sort out all light atoms completely in a single operation, as the mass spectrograph is capable of doing, but merely produces a mixture in which the number of light atoms has been slightly increased. There are many different ways of producing such a slight enrichment, and most of them have been known for a long time, but had never been used on anything but a very small scale. We shall describe some of these methods in the next section.

**3. METHODS OF ISOTOPE SEPARATION.** The first element for which isotope separation had been carried out on a commercial scale was hydrogen, although it was one of the last elements in which the existence of isotopes was proved. In addition to the common hydrogen atom of weight 1, which in fact we used as a standard for comparison with other atoms, it was found by Urey and his collaborators that a very rare isotope of weight 2 existed. Ordinary hydrogen contains only one heavy hydrogen atom to every 5,000 atoms of weight 1, and for this reason the heavier isotope had escaped detection for a long time.

The isotopes of hydrogen represent a rather exceptional case, because the difference in weight of the two isotopes is very large, the one being twice as heavy as the other. As a result, it is possible to detect differences even in the chemical behaviour of the two isotopes and it is, therefore, often customary to talk of the heavier atoms as though they made up a separate chemical element that is called "deuterium". This would seem to be a contradiction to the fact which we noted before that the chemical action of an atom depends merely on the charge on its core and that, therefore,

isotopes ought to be quite indistinguishable in chemical behaviour. The explanation is as follows: Consider a chemical compound of hydrogen and some other element, say the combination of 2 hydrogen and 1 oxygen atoms into a water molecule  $H_2O$ . This molecule forms because there are attractive forces between the oxygen and hydrogen atoms, which tend to put the hydrogen atoms into positions adjacent to the heavier oxygen atoms; we might think of the molecule as one of those figures that modern sets of toys encourage children to make up—a big sphere in the centre with two small spheres joined to it by little sticks, the whole being fixed together quite rigidly. However, modern atomic theory teaches us that light particles have a dislike to staying fixed in a permanent position. For this reason, for example, electrons, which are extremely light, are never found in any definite place within the atom, in particular not near its centre, in spite of the electric attraction, but roam round over a region of considerable extent. This same tendency still exists for hydrogen atoms, although to a much smaller extent, and has the result that the hydrogen atoms in a water molecule will not stay in fixed positions but will wobble a little in the neighbourhood of their equilibrium positions. This phenomenon is usually referred to as "zero-point vibration" to distinguish it from the motions of the atoms that are caused by heat, whereas the motion described here persists even at the absolute zero of temperature. Now, since the phenomenon is more pronounced for lighter particles, the zero-point motion will be stronger for ordinary hydrogen atoms than for heavy hydrogen. Therefore, a molecule of "heavy water" will differ from an atom of ordinary water by having less vibration in the heavy hydrogen, although the chemical forces are the same in each case. This means that the ordinary water molecule is a little less stable and can be broken up a little more easily by action from outside than the heavy water molecule.

This fact is the basis for a number of different methods of separating heavy water from ordinary water. Historically, the first process to be so used was the electrolytic method which was adapted to this purpose by Urey. Urey noticed that if water is split into hydrogen and oxygen by passing an electric current through it, the hydrogen gas so collected contained a somewhat lower proportion of heavy hydrogen than the original water, whereas the remaining liquid water was somewhat enriched in deuterium. In principle one could apply the cascade process to this method, but in this case, since the raw material is plentiful, it is best to start by electrolyzing a very large quantity of water until only a small fraction of it is left. This will be well enriched in heavy water and make a good starting point for the cascade process. Actually, such residues of large quantities of water that has been electrolyzed are found in many commercial electrolytic plants and all commercial processes for the production of heavy water start from such residues.

It might be worth noticing in passing that the property which makes the production of heavy hydrogen fairly convenient in fact delayed its discovery, because the first work on mass spectrography that was done with a view to looking for isotopes of hydrogen had been done with hydrogen produced by electrolysis, and we have seen that such gas is particularly poor in heavy hydrogen.

The question may now be asked whether the same principle can be applied to other elements and in particular to uranium. Indeed a search was continued for a long time for chemical methods that would allow of the separation of the uranium isotopes or for chemical compounds which might be slightly more or slightly less stable according to the isotopes of which they were made. No such process was found, and it is not surprising that this should be so, because, as we have seen, the only difference in the chemical behaviour of isotopes is due to the persistent wiggling or

zero-point motion of the atoms. This effect gets progressively smaller as we go to heavier atoms. In uranium, whose atoms weigh 238 times as much as hydrogen, this motion is very much weaker and, moreover, since the atoms differ only so slightly in weight (3 parts in 238) this already very weak motion is almost the same for both isotopes. In addition, any chemical effects produced in this way are noticeable only at very low temperatures at which the heat motion of the atoms is not larger than the "zero-point vibration". In hydrogen, where the zero-point motion is still fairly substantial, this causes no difficulty; but in uranium, it would force one to go to temperatures so low that all known uranium compounds are frozen and do not undergo any chemical reactions at all.

Chemical methods can be applied to some of the lighter elements if one desires to separate their isotopes, but with increasing atomic weight the method gets increasingly more difficult and is already quite impracticable for atoms of medium weight.

Once such chemical methods have been ruled out, we are left chiefly with mechanical devices. The simplest of these, in principle, would be to sort atoms by their weight rather like the picture of shaking tennis balls in a box which we discussed in the previous section. One might think, for example, of a tall column of some suitable gaseous or liquid compound of uranium which was left standing until the light uranium could be skimmed off the top like the cream from a milk bottle. No doubt this method would work in principle, but it is made impracticable by two facts. The one is that the heat motion of the atoms (like our continued shaking of the boxes) tends to mix up the atoms again and therefore to undo the effect of the different weights. Hence we would need, for complete separation, a column many miles high. For example, the oxygen and nitrogen contained in ordinary air consist of molecules

whose weight differs by two units, i.e. by almost as much as the uranium isotopes. Nevertheless, they do not get appreciably unmixed in the atmosphere between sea level and say 10,000 feet up. Otherwise, there would be no oxygen left on high mountains and life there would be impossible.

The height which is required for such a column would depend on the temperature. If we cool the whole column, the heat motion is less and the atoms will sort themselves out over a smaller height difference, but we cannot go far this way because no liquid uranium compound is known below room temperature, and gaseous compounds condense unless they are kept at such low pressures that the whole amount handled in the column is extremely small. In the solid state, on the other hand, atoms are not free to move around and the process would not work.

The second fact is that the great height of the column means more than a great practical inconvenience, because for a very tall column, the time for which one has to leave the material there until it comes into equilibrium, i.e. until the light atoms have migrated to the top and the heavier ones to the bottom, becomes very large. Actually, such a column could only be skimmed after some thousand years, and this, clearly, ruins the whole idea.

However, the picture is changed if we improve on the help of the force of gravity as provided by nature and produce "artificial gravity", as is done in a centrifuge. It is well known that the process of separating cream from milk can be made both more rapid and more efficient by using a centrifuge. The centrifugal force in such a centrifuge takes the place of gravity, but can be much more intense, and it would seem that a plant for separating the isotopes of uranium by centrifuging is not an impossibility. In fact, such a plant was under very serious discussion in the American project. Like all the other methods we shall talk about,

it is not an easy task, because of the large number of high speed centrifuges required for the job; these are very delicate pieces of machinery and need precision methods for their construction.

Even with the fastest practical speeds, it would not be possible to produce pure 235 in a single operation of a centrifuge, but it is possible to produce a considerable enrichment, and several units would have to be combined in the cascade scheme discussed before.

4. DIFFUSION AND OTHER METHODS. Another method that was known to be suitable for the separation of isotopes relies on the diffusion of gas through porous membranes. The reasoning behind this is as follows: It is well known that the atoms or molecules of a gas are moving about at speeds which are greater the higher the temperature and, in fact, heat is just the effect of this fast motion of molecules. At any given temperature the speed with which the molecules move depends on their weight. The speed varies inversely as the square root of the mass, so that if one molecule weighs four times as much as another its speed, at the same temperature, will only be one-half that of the lighter molecule. This means that if gas is allowed to escape into an empty space or a space where the gas pressure is lower, the lighter molecules will tend to run faster than the heavier ones and to get ahead. Now this does not mean that if we discharge, say, a storage tank of compressed air through a pipe, more nitrogen will escape than oxygen. Here, in their passage from the tank, molecules have frequent opportunity to collide with each other, and hence the oxygen molecules, which tend to be a little more sluggish, will be hustled along by the nitrogen and this, in turn, will delay the progress of the faster nitrogen atoms. The situation is similar to a dense crowd of people walking through a passage, where everyone will

make progress at the same rate even though some people may want to walk slowly and others may be in a hurry.

The high natural speed of the lighter molecules can make itself felt only in conditions in which the progress of each individual molecule depends only on that molecule itself and is not influenced by collision with the others. This is the case, for example, if gas "diffuses" or seeps through porous material such as clay in which it has to pass through a large number of very fine pores; the point being that each gas molecule collides more often with the solid material than with other molecules. This will delay its progress very much, and the rate of gas flow is, of course, much less than it would be through bigger openings, but these obstacles are independent of the presence of the other molecules and there is, therefore, much less tendency for the faster molecules to speed up the slower ones and vice versa, and each molecule will move at a rate that depends on its own natural speed.

This method had been successfully applied by G. Hertz to the separation of isotopes of the rare gas neon, in a laboratory apparatus which gave a few litres of gas in a run of several hours. Hertz used unglazed porcelain tubes as the porous membranes, and he had again to use the cascade arrangement. The isotopes of neon have atomic weights of 20, 21 and 22. In other words, the lightest and the heaviest differ by 10 per cent in weight and their velocities at a certain temperature will differ by 5 per cent. Hence, in the most favourable case, where we have made the pores in the membrane so small that the collisions between gas molecules do not matter at all, the rate at which the molecules diffuse through the membrane differs by 5 per cent. In other words, if we start with a mixture containing say 10 per cent of the light isotopes, the gas seeping through the membrane will have been enriched by

5 per cent of the original number of light molecules and will contain  $10\frac{1}{2}$  per cent of the light isotopes. If this gas is passed on to the next stage of the cascade, the light fraction obtained from that next stage might have a concentration of 11 per cent, and so on. It is seen that even in this case a large number of steps are required before we have practically purified the lighter isotope.

In the case of uranium the problem is more difficult because the weights differ only by roughly one per cent and, hence, the maximum increase in the concentration in each stage would, in most favourable conditions, only be approximately  $\frac{1}{2}$  per cent. In other words, for ideal conditions the fraction of light atoms would, per stage, increase by something like a factor 1.005. Since this fraction is only 0.7 per cent to start with, we see again what a formidable undertaking is presented by our problem. Moreover, uranium itself is not a gas ordinarily but a metal, and to vaporize it would require temperatures for which no porous membranes or pumps could be found. It has, therefore, to be used in a compound, and of the compounds of uranium, only one is a vapour in conditions that are at all suitable for practical purposes. This is the hexafluoride of uranium, consisting of 6 atoms of fluorine combined with one atom of uranium. The atomic weight of this combination is 352 for the heavy uranium and 349 for the lighter. The weight difference is, therefore, even somewhat less than one per cent.

The properties of this compound make it an extremely unpleasant substance to handle. It is highly corrosive and many of the materials ordinarily employed in constructing chemical apparatus would be attacked by the gas. This is bad not only because it will gradually destroy any apparatus in which such materials are used, but also because in the reaction the gas itself decomposes, and in place of the volatile uranium compound we are left with a solid de-

posit on the wall which will be lost from the process. Since, in the very many stages of a separation plant, the gas has to circulate for a very long time before it eventually finds its way into one of the end stages, one cannot afford to lose even a small fraction of the gas on the way; otherwise there would be no product left at all when one finally got to the end. In addition, such solid products may also form dust which will tend to settle in the fine pores of the membranes and make them unusable. One of the worst enemies of uranium hexafluoride is moisture, which will not only react with it and decompose it, but at the same time liberate from it fluorine in combinations such as hydrofluoric acid, HF, which is an even more highly corrosive substance. Throughout all the stages of a separation plant, the gas must, therefore, be extremely carefully protected from contact with ordinary atmospheric air which is always moist.

In order to collect the gas that has passed through the membranes and compress it again to make it ready for passing through the membranes of the next stage, pumps are required, and these again must be of a very unusual design, since the construction materials ordinarily used for pumps, and, for example, the oil and grease normally used to lubricate them and prevent leakage, would be attacked by the gas very rapidly.

The size of the pumps required depends very much on the perfection of the membranes one uses. The connection is as follows: We have seen previously that it is necessary that the pores be so small that, in their irregular motion through the pores, molecules should run into a pore wall more often than they run into other molecules. Now, collisions between molecules depend on the density of the gas. If the gas is denser, molecules collide more frequently, and hence for each kind of membrane there is a greatest gas density or gas pressure for which they will work satis-

factorily. If we make a better membrane with smaller pores, we can afford also more collisions between molecules and, therefore, a higher gas pressure. Now the size of a pump does not depend much on the actual mass of gas it handles, but chiefly on its volume. If we have to work at lower pressures the same amount of gas will occupy a larger volume and therefore need larger pumps.

To summarize, we can see from this description that, in principle, the process of separating isotopes by diffusion is simple enough, but that the practical problem involved in finding membrane materials, construction materials, lubricants and seals that would stand exposure to the corrosive gas, in designing pumps, in building a plant containing all these pumps and keeping it completely protected from external air and of controlling the flow of gas through all the many stages of the cascade scheme, represents an enormous undertaking.

It is not at present possible to describe the many ingenious inventions that were made in the course of overcoming all these difficulties, but it is by now common knowledge that the difficulties were overcome by the co-operation of large teams of scientists and engineers, and that a plant working along these lines is in operation.

There exist other methods which depend on the different speeds of isotopes of different weight; one of them being a method also developed by Hertz, which uses the diffusion of gas through a stream of another gas rather than through a membrane. Another method, due to Hevesy, uses the fact that if you evaporate a liquid while keeping the space above the liquid evacuated, the lighter components of the liquid will evaporate more quickly, since there again the motion of the vapour molecules is more rapid. These and many other methods were discussed and discarded as less suitable to the problem in hand than the diffusion through membranes.

One method that came to mind immediately when the problem first arose was that of thermal diffusion of a gas. This term is applied to a peculiar phenomenon that is found in most gases and consists in a tendency of lighter molecules to go to the hotter part of a tube and for the heavier ones to go to the colder end, if the two ends of the tube filled with gas are kept at different temperatures. The particular attraction about this scheme is that Clusius and his collaborators had invented a very neat trick by means of which one could avoid the use of a large number of separation stages in a cascade arrangement and could effectively have a large number of stages in a single tube. The trick works in the following way. Imagine two vertical walls close together—one hot, the other cold. Then, because of the thermal diffusion effect mentioned, the gas near the hot wall will be slightly enriched in the light isotope. At the same time, because it is hotter, this gas is at a lower density and tends to float up, whereas the colder gas tends to sink down. The result is, therefore, a circulation of the gas up the hot wall, across the top and down the cold wall. Now, since the gas near the hot wall is slightly enriched, the upward current carries an excess of light isotope and there is a net flow of light isotope towards the top and light gas will accumulate at the top until a difference in composition has been established which, by the natural tendency of the gases to mix again, will compensate the upward flow of light gas. This arrangement is equivalent to a large number of individual stages, that number being roughly equal to the ratio of the height of the column to the distance between the walls. As the height can easily be many feet and the distance between the walls a small fraction of an inch, we see that this scheme is equivalent to a great many stages, and one need only connect a few such columns to obtain a reasonable enrichment. In practice, the scheme of Clusius does not use plane walls but concentric tubes,

the inner one being heated by a flow of hot liquid or gas, the outer one being cooled.

Unfortunately, measurements of the thermal diffusion effect in uranium hexafluoride showed immediately that in this particular gas the effect happens to be extremely small. The causes for the effect are complicated and depend a great deal on the nature of the molecules and the forces between them, so it is not possible to predict beforehand whether it is going to be large or small in any particular gas. In this gas, however, it turns out to be so small that a plant built on this principle would be quite prohibitive in cost, power consumption, and size, even though it has the great advantage of simplicity and contains no moving parts.

Many people had studied the same principle as applied to liquids, and had always found that use of liquids was very much less efficient than use of gaseous compounds, the chief reason being that liquids have a higher heat conductivity, so that if a gap between a hot and a cold wall is filled with liquid, much more heat is supplied on the hot side and more taken away by cooling on the other side to maintain the same difference in temperature. It was, therefore, thought that the same would be true in the case of uranium hexafluoride, but experiments carried out by Abelson gave the surprising result that, while the thermal diffusion coefficient of gaseous uranium hexafluoride was extremely small, that of the liquid happens to be rather large, and that using liquid hexafluoride it was not impossible to build a plant of reasonable dimensions. Even so, it would have been impossible to rely on such a plant entirely for the production of pure Uranium 235. Even for a moderate enrichment, the plant would consume very large amounts of heat, for example in the form of steam. There was, however, during the completion of the separation plant at Oak Ridge, Tennessee, a period when a large capacity for steam production was available while the plant that was to use

it had not been completed. It was then decided to erect a thermal diffusion plant which would use this steam and produce in this way enriched material that would lighten the burden of the electro-magnetic plant which was then already in operation.

Lastly, we should here mention another method which was investigated at length, that is the electrolytic method. It is well known that if an electric current is passed through a solution of a salt in water, the electric charge is carried through the solution by the motion of charged atoms or molecules. Just as in the case of a gas, there is some difference in the speed with which the lighter or heavier molecules tend to move, and, in general, the light ones will get slightly ahead of the heavier ones. A nice trick to make this method convenient in practice was suggested independently by several people. It consists in letting the solution pass slowly through the tube in a direction opposite to that of the electric current and arranging the strength of the electric current in such a way that the charged molecules will just stay put. This balance between the backward flow of the solution and the forward flow due to the current will be slightly different for the light and heavy isotopes and in any given part of the tube the light isotope will gradually drift forward and the heavy isotope back. H. London succeeded in measuring the magnitude of this effect and getting a slight separation with it. It turned out, however, that the effect was not favourable enough to compete seriously with other methods of separation.

**5. THE ELECTRO-MAGNETIC PLANT.** All the methods discussed in the three preceding sections are based on principles which allow only a slight enrichment in every stage of the process and which, therefore, have to be applied repeatedly in a large number of stages to obtain nearly pure U-235. We have already seen that, in principle,

the mass spectrograph is capable of performing the separation completely in one step, but it always appeared that the translation of this delicate laboratory instrument into industrial practice on a large scale would present insuperable difficulties. However, E. O. Lawrence started research on this problem. The method he was using was essentially that of the mass spectrograph. The main modifications that had to be made were those to improve the economy of the process. In the ordinary mass spectrograph only a very small fraction of the gas sample that is put in for analysis is actually charged up by collisions (ionized) so that it can be accelerated to form the beam that goes through the main part of the apparatus. The rest remains in the form of neutral atoms which spread through the tube and are carried away by pumps that keep the tube evacuated. It is evidently important to keep the fraction of the gas that is actually utilized in the beam as large as possible and to reduce the amount that has to be dealt with by the pumps and serves no useful purpose. It is also necessary to make provision to recover any material that has settled as a solid deposit on the walls and other parts of the apparatus, since with the large quantities handled by an actual plant, one would otherwise not only have serious losses of raw material but would also soon completely clog the apparatus. Moreover, the magnetic fields necessary for the functioning of the apparatus require large electro-magnets which represent the most expensive part of the equipment. In order to utilize these as well as possible, it was necessary to make the beams of charged atoms as intense as possible and also to get as many of those beams as possible within the field of each magnet. In addition, very high precision is required to obtain magnetic fields of just the right strength and shape and to have the receivers for the product in just the right positions. This would normally require careful work by skilled physic-

ists in a laboratory. Provision had to be made to have these adjustments effected by less highly trained personnel and in the conditions of a large plant. And, lastly, a very complicated chemical plant had to be provided to turn the raw material into the compound used in the separation plant and to convert back to the same compound the many different amounts recovered from gas carried out by the pumps from deposits inside the apparatus, etc., which had usually undergone chemical reactions with the materials of the wall and with other impurities and, therefore, needed chemical treatment.

Again, only an enormous effort of scientists and engineers made the completion of this task possible and, in spite of the fact that the step from a delicate laboratory instrument to a large-scale plant is even larger and more unexpected here than in the case of a diffusion plant, the electro-magnetic plant was, in fact, the first plant to produce useful amounts of uranium 235.

Although it would be possible, in principle, to carry out the whole separation in one stage, it turns out that this is not convenient in practice, because the beam carrying the heavy isotope is so much stronger than that carrying the light isotope that very high precision would be needed to get perfect separation in the first step, since one has to avoid any spread on each beam which would mix up even a small fraction of the stronger beam with the weaker one. This would be possible, but it would severely limit the rate at which material could be handled in each unit, and it pays, therefore, to use, instead, a plant that in the first stage will only produce an incomplete separation and to pass the material thus obtained through a second stage, which can now be smaller since it handles a much smaller amount of material, and to complete the separation in the second stage. This second stage is much less of an engineering problem because of its smaller size, but it has to be much

more carefully designed because it is more important that the recovery of material from it be complete, since the material fed into this stage is very valuable, representing the output of the first expensive plant, and the loss of even a small fraction of this material would be serious.

There exist designs for devices working on other principles which are similar to the electro-magnetic plant, in that they are capable of producing appreciable separations in a single stage, and which use atomic beams running in conditions of high vacuum so that each atom keeps its own path regardless of the presence of others. The most interesting of these is the "isotron" which uses a rapidly oscillating electric field which will accelerate and decelerate in rapid succession a beam of charged atoms, when again the light atoms will respond somewhat more quickly to the field than heavy atoms. One can arrange matters in such a way that if a continuous stream of atoms leaves the source they will all meet at a certain point further down the tube because the later arrivals have passed the field at a time when it was accelerating and have been speeded up, whereas the earlier ones passed at a time when the field tended to decelerate them and have been held back. Because of the different response of the different isotopes the point where the atoms will be accumulated is different for the light and the heavy isotopes, and if arrangements are made to draw off atoms at the right instant from the right point in space, one can arrange to collect preferentially the light ones. This device was developed by R. R. Wilson and probably could also have been turned into a plant of industrial dimensions, but the electro-magnetic plant was more promising and the isotron was abandoned in its favour.

6. CONCLUSION. We have attempted to give a brief sketch of the principles involved in the known methods of

isotope separation and of the enormous scale of the operations required for this. All these plants serve the common purpose of producing in a pure or nearly pure form the isotope uranium 235. The next article will describe similarly the plant that produces the element plutonium, which is the other possible atomic fuel. Large-scale plants for both purposes were pushed to completion because it was not known at that time which of the two fuels would be more suitable for making bombs nor how long the actual completion of each plant would take.

In the future, we may hope that the importance of making bombs will gradually be superseded by that of releasing atomic energy for peaceful purposes. In this, the plants are at a disadvantage because the "piles" described in the next article produce power directly, starting from uranium in its natural form. Nevertheless, for many applications it will be essential to have small and concentrated power units which have to use pure active material, i.e., pure or nearly pure plutonium, or pure or nearly pure uranium 235. It is too early yet to see through the many factors that govern the economy of these two possibilities, and it is, therefore, not known now whether separation plants will remain a permanent feature of atomic energy projects or whether their function in producing the material used in the first atomic bomb is now a matter of history.

## THE TAMING OF ATOMIC POWER AND THE PRODUCTION OF PLUTONIUM

*By H. L. Anderson*

ATOMIC\* ENERGY is not a new discovery, for it was first recognized as an energy source when radioactivity was discovered. Nor is it an unimportant source, for not only is it responsible for a part of the earth's heat (the interior of the earth is kept from cooling by radioactive heating), but also, if we go back a step, the wood, the coal, the petroleum and the water power, all our common energy supplies, derive from the sun; and the evidence is now quite strong that the energy which is developed by the sun is largely due to the nuclear reactions taking place there. But this energy, instead of being produced by the disintegration of nuclei, is released by the building-up of the light atomic nuclei. Astrophysical data show that the sun contains a large amount of hydrogen. It is this hydrogen which combines in a succession of nuclear reactions to produce helium.

These reactions do not take place spontaneously on earth, because, in every case, the interacting particles are charged and tend to repel one another. In the laboratory, a few of the nuclei can be accelerated to sufficient speeds so that the particles can get close enough together to react. This permits us to study the reaction, but not to use the energy. Inside the sun the temperature is of the order of 20 million degrees, so that, because of their thermal agitation, the atoms move with sufficiently great velocities

\*Atomic energy is a popular term for what may be more strictly termed nuclear energy.

to penetrate the strong electrical repulsive force field and come close enough together to react. The release of energy maintains the high temperature so that the reaction continues, in much the same way as coal is burned.

It appears, then, that atomic energy is the principal source of energy for the earth. The coal, petroleum and wood which we burn were all made by photosynthesis of carbon dioxide and water using the sun's energy. By evaporation of the water of the oceans and the lakes, the sun provides us with our water power.

**EQUIVALENCE OF MASS AND ENERGY.** In every reaction in which energy is liberated, a corresponding amount of mass is lost. Thus, we might say that the energy comes from the mass in accordance with Einstein's relation

$$E = mc^2$$

where  $E$  is the energy in ergs,  $m$  is the loss in mass in grams, and  $c$  is the velocity of light,  $3 \times 10^{10}$  centimetres per second. The relation holds just as faithfully in chemical reactions as it does in nuclear reactions even though the mass changes for the chemical reactions are vanishingly small. The Einstein relation tells us *where* the energy comes from—what we have said about the forces which act gives a little more insight into *why* the energy appears. When all the masses of the reacting components are known this formula provides a simple way to calculate the energy release. In many cases it is not easy to measure the change in mass which takes place and it is generally simpler and more accurate to measure directly the heat liberated, or the ionization produced. However, the formula does give the maximum possible energy which would appear if all the mass were converted into energy.

**ENERGY FROM THE FISSION OF URANIUM.** If the whole of one gram of mass (it makes no difference of what)

were converted into energy we should obtain  $2 \times 10^{13}$  calories. In the fission process the energy release has been measured and is approximately  $2 \times 10^{10}$  calories\* per gram (ten million kilowatt-hours per pound). This is about two million times more than the energy which is released in the burning of equal weights of petrol or high-grade anthracite coal. In the case of the combustion of coal, we say that the atoms of oxygen and carbon which enter into the reaction are attracted to one another when they are brought together and energy is released in bringing about their combination. More precisely, there are forces which act between the electrons and the nuclei of the atoms which make up the molecules of matter so that in some combinations the energy required to hold them together is less than in others. The excess energy is released whenever the transition from a less to a more stable configuration is brought about. These general notions apply in the case of nuclear reactions as well. The forces between the neutrons and protons, constituents of the nucleus, are very many times greater than those which act between the electrons and the nuclei of the molecules. For this reason nuclear transformations involve much greater energy changes than molecular transformations.

In the fission of uranium the heaviest nucleus is split into two approximately equal parts. The neutrons and the protons which make up the uranium nucleus are, however, in a more stable configuration when they are divided among the two fragments which are formed in the fission. The energy which is released is, in fact, a measure of this improved stability. The excess energy appears as kinetic energy and is evidenced in the great speeds with which the

\*The calorie is the amount of heat energy required to heat 1 gram of water 1 degree Centigrade from 15° C. There are  $4.18 \times 10^7$  ergs in one calorie. Symbols such as  $10^7$  or  $10^{10}$  are the scientist's shorthand for a 1 followed by 7 or 10 zeros respectively.

two fragments fly apart. In addition to the two fragments it is known that two or three neutrons are also given off. The neutrons provide the mechanism whereby the fission reaction can be propagated to very large numbers of the uranium nuclei and so make it possible for large amounts of energy to be released, as we shall see.

**THE FISSION PROCESS.** The fission process can be brought about by bombarding uranium with neutrons. The neutron, being an uncharged particle, has little difficulty in entering the uranium nucleus. It is frequently unnecessary to use neutrons of very high velocities as would be the case for the charged particles. In fact, the slower the neutron is moving the more readily is it absorbed in the uranium nucleus.

It is necessary to distinguish between the various kinds of uranium nuclei which there are. Insofar as chemical properties are concerned, all the isotopes of uranium behave in the same way because they all have 92 electrons outside balancing the charge from the 92 protons which their nucleus contains. The different uranium isotopes differ in the number of neutrons which they contain. There is a light isotope U235 which contains 143 neutrons, and there is the heavy isotope U238 which contains 146 neutrons. There are also other isotopes, containing different numbers of neutrons, some of which can be made by nuclear reactions, as we shall see. In their nuclear behaviour, the isotopes may behave quite differently from one another. The two isotopes which we have mentioned are the most abundant which are found in nature, but the heavy uranium is 140 times more abundant than the light uranium.

The light isotope of uranium, U235, is the only nucleus found in nature which can be fissioned by slow neutrons. It is possible to produce new nuclei which also have this property. Slow neutrons are absorbed in the nucleus of the

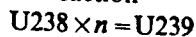
heavy uranium, but fission does not take place because the isotope which is formed, U239, remains stable against fission unless the neutron brings with it a fair amount of energy to start the fission process. The same is true in the case of the thorium isotope Th232, which will only fission provided that the incident neutron is sufficiently energetic.

Of the other heavy elements which are fairly abundant on earth, both bismuth and lead have been studied and no fission has been observed with either. It is most improbable that elements still lighter than lead would show this phenomenon. Thus, energy release is possible in the building up of light elements and in the breaking down of heavy elements, and one might guess, correctly, that in the medium-weight elements such as iron, energy release does not take place in general because their nuclei are the most stable.

**PRODUCTION OF PLUTONIUM.** Fission is produced by neutrons in only a few nuclei, but in almost every nucleus the neutron may be more or less readily captured. When captured, the neutron converts the nucleus which it enters into the next heavier isotope. When this new isotope is not naturally stable it is radioactive and in most cases will ultimately emit a beta particle, and be converted, thereby, to the next higher element in the periodic table. We will refer to the process forming the next isotope as the capture process, to distinguish it from the fission process. When we say that a neutron is absorbed we shall mean that it is either captured or has produced fission. The neutron may strike a nucleus and instead of being absorbed may be re-emitted. This neutron re-emission is called scattering. The scattering is elastic if kinetic energy is conserved, or inelastic if some of the kinetic energy of the neutron is used to change the state of excitation of the nucleus.

Plutonium is produced from the capture of neutrons

in the heavy uranium U238. The process takes place most readily with slow neutrons, and starts with the formation of U239 according to the reaction



The U239 is radioactive and emits a beta particle after an average time\* of 34 minutes, to form the neptunium isotope Np239. This isotope is also radioactive and by emitting a beta particle after an average time of 3.3 days is converted to the plutonium isotope Pu239. The plutonium formed in this way does disintegrate by the emission of alpha particles, but at such a low rate that for practical purposes quantities of it can be accumulated, and its properties studied. Its significance in our discussion is that, like U235, Pu239 is also fissionable by slow neutrons.

**NUCLEAR CHAIN REACTION.** While a great number of nuclear reactions have been studied and are known to yield sizeable amounts of nuclear energy, it was possible to bring the reaction about in only a few atoms at once. we want to produce copious amounts of energy we have to contrive to make the reaction propagate itself so that a large number of the atoms will be involved together.

The burning of coal is a thermal reaction which will not proceed below a certain kindling temperature; but once this ignition point is reached the heat generated is usually sufficient to maintain the mass at a sufficiently high temperature for the burning to proceed as long as oxygen is able to come in contact with carbon. In nuclear reactions which proceed in the same way, as they do in the sun and the stars, the ignition temperatures are much higher. We have not learned how to achieve in a large mass

\*This average time is not identical with the half-life of the radioactive substance, but is longer by a factor of about 1.44. How half-lives are measured is described in the article on "The Tools of Nuclear Physics."

of material, temperatures high enough for such thermonuclear reactions to propagate themselves.

In the fission process we have available another mechanism whereby the reaction may propagate itself, without the need for high temperatures. The fission is brought about by the absorption of neutrons, and in the process of fission more than one neutron is emitted. If the new neutrons can efficiently make contact with other uranium nuclei, it is clear that the fission of uranium nuclei can be continued until a very large number of the uranium nuclei have been disintegrated.

Let us study a simplified example. Imagine a large mass of an easily fissionable substance like U235 into which we introduce one neutron to produce one fission. This fission produces, let us say, two neutrons which are then absorbed elsewhere in the mass. Suppose both of these in turn produce fissions so that now 4 neutrons in all are emitted. This process can continue and the number of neutrons produced by the mass will be multiplied manifold. Since the neutrons travel at high speeds, and since they do not have to travel very far to be absorbed, this multiplication can take place very rapidly and in a very short time an enormous number of nuclei will have undergone fission and large amounts of energy will have been released.

The neutrons which are emitted upon fission have a velocity of about  $1.5 \times 10^9$  centimetres per second, and since they have to travel only some centimetres before they are absorbed again, their number will increase by a factor of two, in the present example, in a time of the order of  $10^{-8}$  seconds. In a millionth of a second, therefore, the number of neutrons would have increased enormously and some hundreds of tons of the light uranium would have fissioned. Of course, this is a much greater amount than would ever be caused to react at one time, but it does show that quite large amounts of material could be made to

react in an exceedingly short time. When we realize that the energy release for one kilogram of material is equivalent to 17,000 tons of T.N.T., and the reaction time is even shorter, the explosive power of the fission reactor becomes apparent.

This mechanism is the one which underlies the atomic bomb, but in practice we should not use an indefinitely large mass of uranium. When we consider that the mass of our material must have finite extent we have to realize that some of the neutrons may escape from the mass and not be utilized in the reproduction process. Furthermore, there are competitive absorption processes which absorb neutrons but do not cause fission and hence reproduction.

In natural uranium the capture process in U238 which leads to Pu239 consumes such a large fraction of the neutrons that, even in a very large mass, few are left to cause fission, and the number of neutrons produced per neutron absorbed is less than one, so that the multiplication of neutrons cannot proceed indefinitely.

**CONTROLLING THE NUCLEAR REACTION.** One rather direct way to reduce the competitive absorption is to reduce the amount of U238 in uranium. This involves an isotope separation which is no simple task, although it has been carried through at great expense and difficulty. It has in this way become possible to make atomic bombs of assemblies of purified U235. (See article on isotope separation.)

Once sufficiently pure fissionable material has been made available, the problem of assembly becomes all-important. How do we bring sufficient material together so that once started, the energy release will take an explosive character and yet be sure that the bomb will not go off prematurely? Neutrons which could initiate the reaction are produced by cosmic rays, they are emitted from some substances

which might be present as impurities, and, in addition, uranium nuclei are known to fission spontaneously, if infrequently. Thus, we may expect that there will always be a few neutrons produced in the assembly and we cannot hope to inhibit the reaction by not furnishing the initial neutron.

What we can do, however, to avoid premature explosion is to balance the production of neutrons by a corresponding rate of leakage, so that there are never enough neutrons in the uranium mass to keep the chain reaction spreading. Clearly the loss of neutrons by leakage out of the mass depends on its shape and size—the relation of its surface area to its total bulk, and below a certain amount of uranium, the critical mass, leakage accounts for the majority of neutrons, and not enough are left to “reproduce” themselves by causing further fissions. The Reproduction Factor is a term to express this briefly and precisely. It is a ratio: the total number of neutrons in one generation causing fission, divided into the number of those neutrons produced by that fission which will go on to cause the fissions of the next generation. Thus in the simple example before, one neutron caused a fission producing two neutrons; each of these in turn caused fissions which doubled the number of neutrons; and the reproduction factor is clearly 2. But if, of every two neutrons produced in a fission, one leaked away, only one would be left to produce a further fission, and the reproduction factor is only 1. In this latter case, the neutron level, and hence the energy production level at which the reaction works, remain constant at whatever they happen to be. Therefore, as long as the reproduction factor is less than 1, as it always must be in a sub-critical mass, a stray neutron cannot set off a divergent chain reaction, and the material remains safely quiescent.

The value of the reproduction factor is simply varied

by changing the ease of neutron escape (leakage) by having the material in two or more subcritical masses which can be brought closer together or separated at will. The closer they come the higher the reproduction factor. The atomic bomb is a device in which the subcritical masses are aggregated very rapidly, so that the reproduction rate for neutrons rises very steeply and an enormous amount of energy is produced in a very short time.

**CALCULATION OF NEUTRON INTENSITY.** There are always a few neutrons being produced inside a mass of fissionable material. We will suppose that we have somewhat more than a critical mass of material but we have removed part of this mass far enough from the rest for the leakage of neutrons to be great enough to bring the reproduction factor below 1. In this case the original neutrons will be multiplied somewhat, but the neutron intensity will finally reach a well-defined value which becomes greater as the reproduction factor approaches 1. Consider a primary source of neutrons emitting one neutron per second in the mass. If we denote the value of the reproduction factor by  $k$ , the first generation will produce  $k$  neutrons per second, these  $k$  neutrons will in turn produce  $k^2$  neutrons per second in the second generation, and so on, so that in all, if  $k$  is less than 1, the total resulting number of neutrons being produced per second will be given by

$$1 + k + k^2 + k^3 + \dots = 1/(1 - k)$$

Thus, if the reproduction factor is 0.9 and if the source of neutrons in the mass yields 1 neutron per second, the above analysis shows that, after a while, neutrons will be produced in the mass at the rate of 10 neutrons per second. By bringing the adjustable part of the assembly closer and closer to the rest of the mass the value of  $k$  can be brought closer and closer to 1 and the neutron intensity can be brought to any desired value.

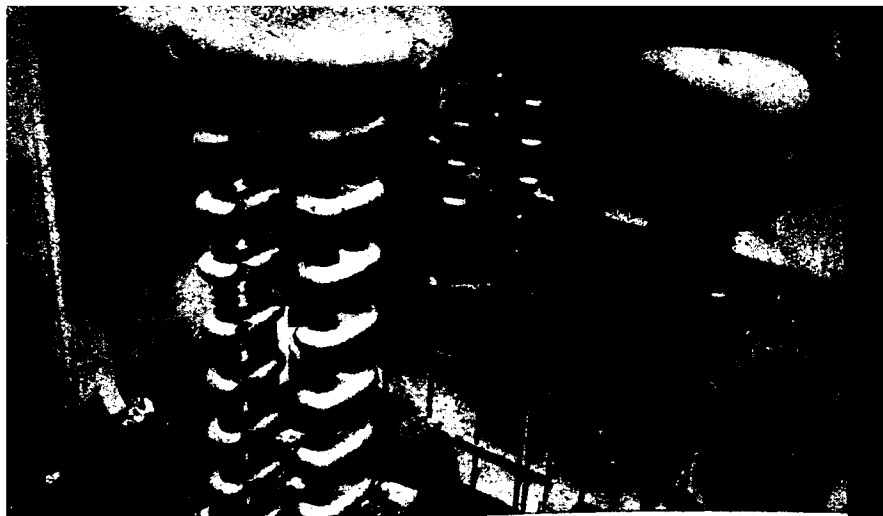


PLATE 1. The two-million-volt generator being assembled at the High Tension Laboratory at Cambridge University. In the background is a million-volt generator used for accelerating deuterons, which pass down the tube on the right into the room under the platform (see plate 2).

PLATE 2. The accelerated deuterons pass down the tube (now seen on the left) and are turned along the gleaming glass tube in the centre by a massive magnet. They are bombarding atoms under the hand of the operator, and will smash some of their nuclei.



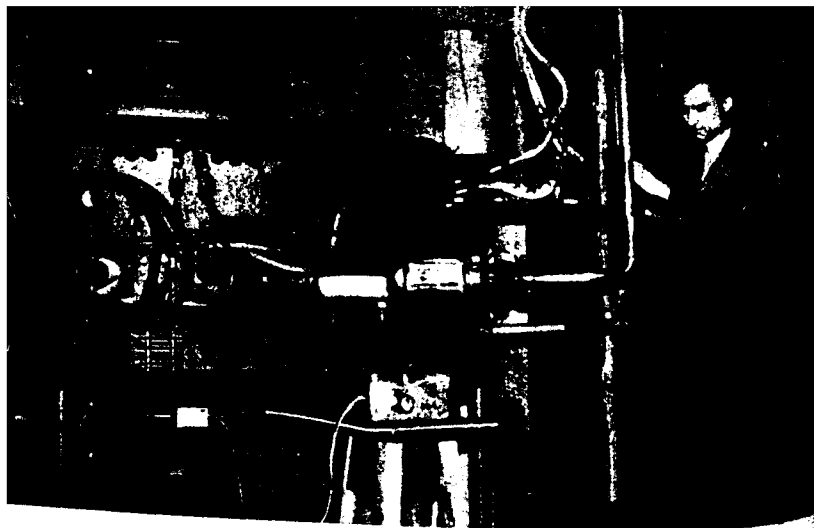


PLATE 3. The first version of the Cambridge cyclotron. The pipes running over the machine carry water to keep it cool (see diagram below).

PLATE 4. Diagram of the cyclotron in plate 3.

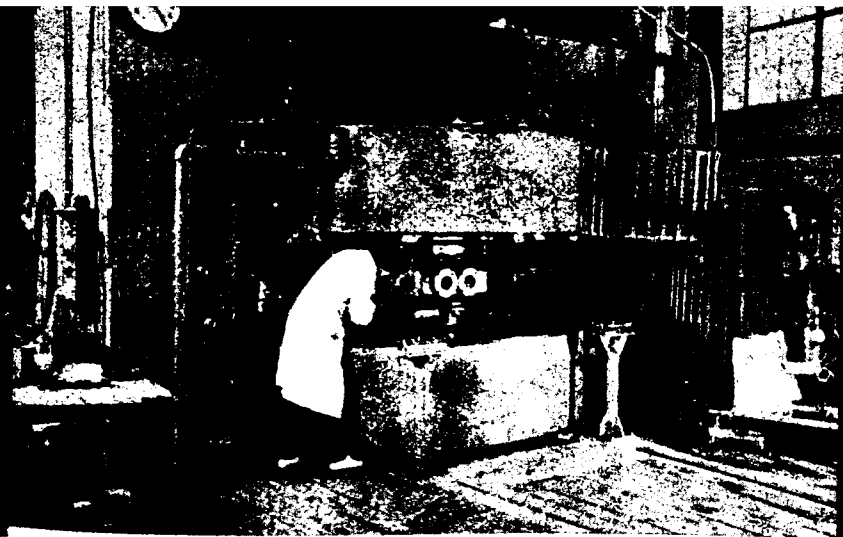
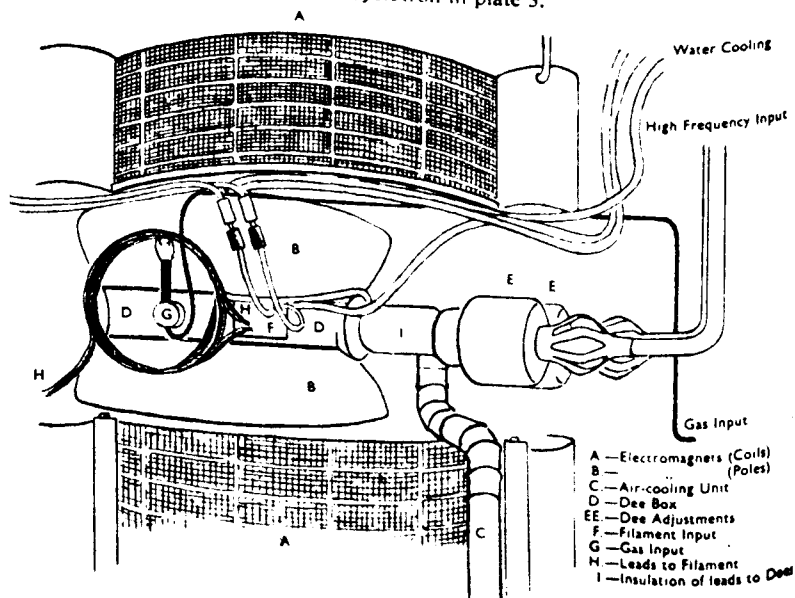
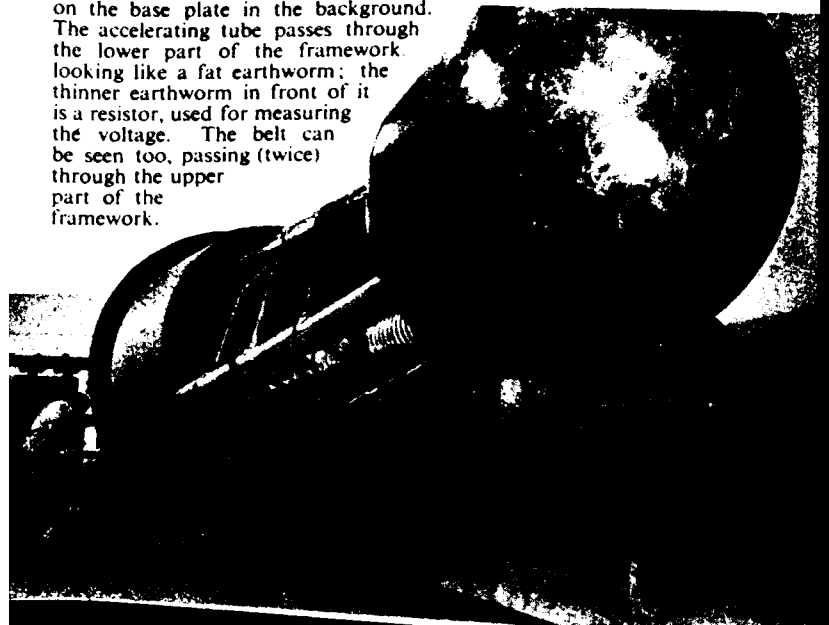


PLATE 5. Tokyo cyclotron, before the war. The scientist appears to be tightening some bolts on the tank, poking his head between the coils. The big rectangular structure of solid steel around the coils is the yoke of the magnet. The destruction of this machine caused great indignation amongst scientists both in this country and America, who did not regard cyclotrons as weapons of war.

PLATE 6. Van de Graaff generator (Notre Dame University) with outer cover removed, and partly dismantled. High-voltage electrode close to spectator, carried by framework mounted on the base plate in the background. The accelerating tube passes through the lower part of the framework looking like a fat earthworm; the thinner earthworm in front of it is a resistor, used for measuring the voltage. The belt can be seen too, passing (twice) through the upper part of the framework.



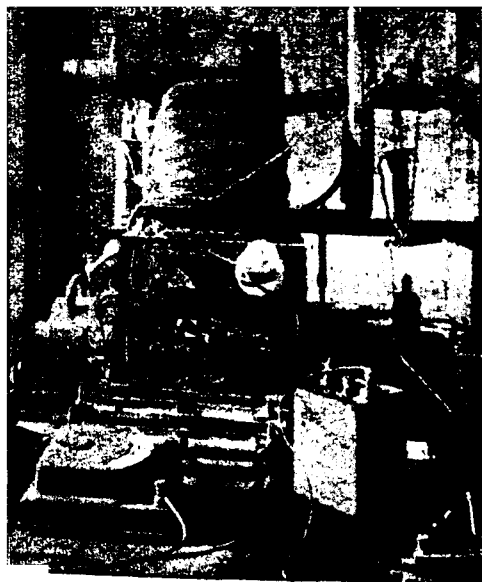


PLATE 7. Aston's mass spectrograph: the second model, built 1935. (*Mass Spectra and Isotopes by Aston: Edward Arnold & Co.*)

PLATE 8. Ions are produced in the discharge tube and pass down the tube to the left, through slits and between charged plates (not shown), pass the poles of the electro-magnet (dotted lines) to the photographic plate PP shown lying horizontally inside the camera. The pea lamp makes a mark on the plate to show how it was placed in the camera. (Diagram of plate 7.)

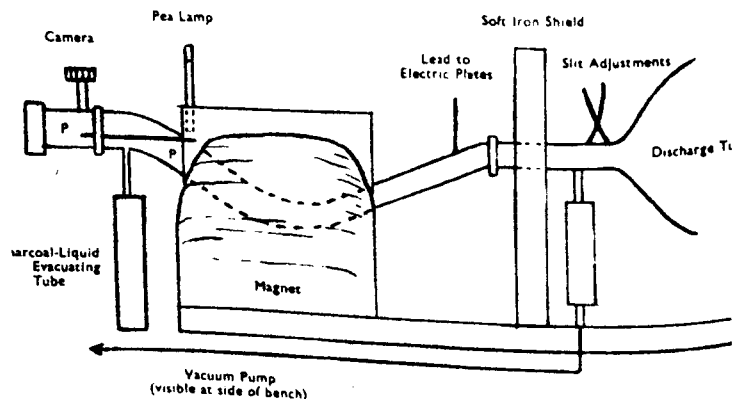


PLATE 9. Typical mass spectra. Each black band is the mark made on the film by the particles of a single isotope; the atomic weights are marked in. (*Mass Spectra and Isotopes by Aston: Edward Arnold & Co.*)

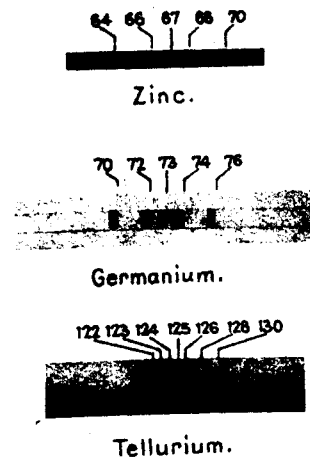


PLATE 10. Electron tracks.

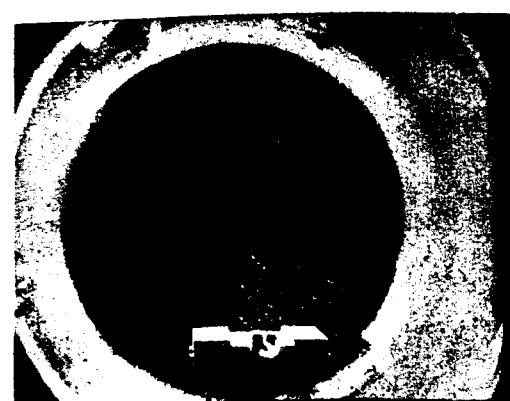


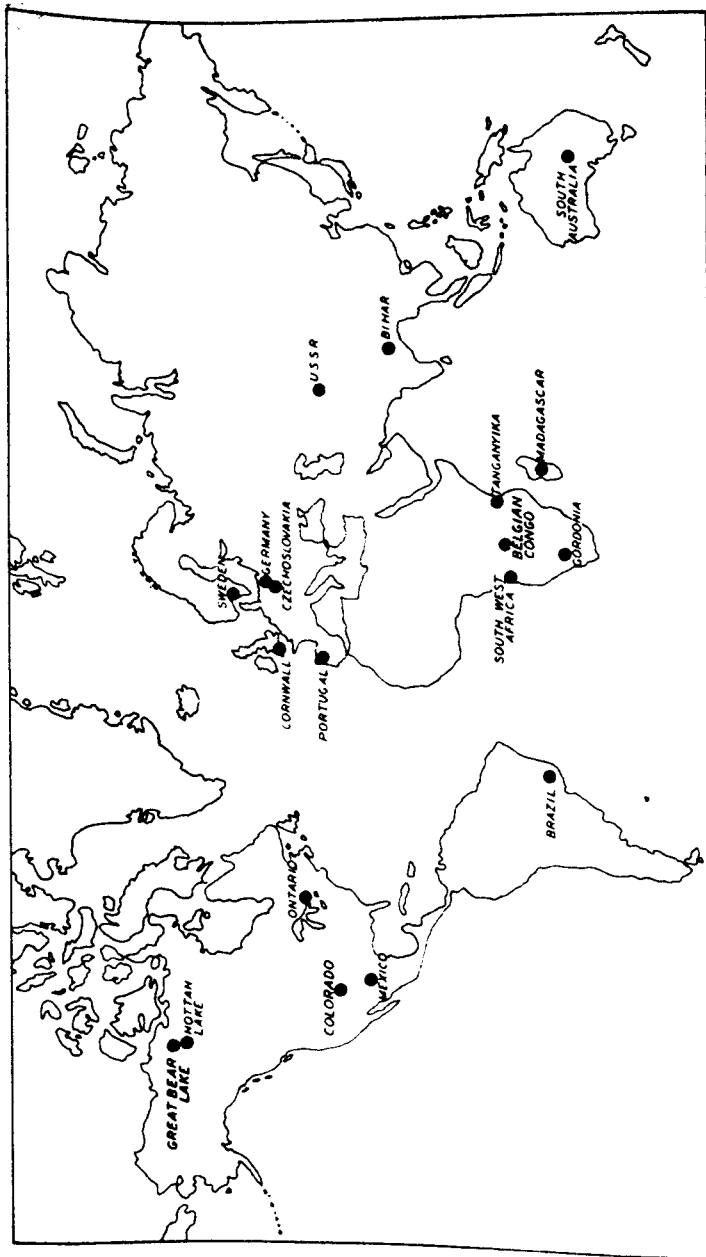
PLATE 11. Alpha-ray tracks. (*Cavendish Laboratory, Cambridge.*)





PLATE 12. The first atomic bomb explodes. To give some idea of size, the outline of St. Paul's Cathedral has been printed in on the same scale. (Copyright in U.S.A. by Julian Mack for the Assn. of Los Alamos Scientists.)

PLATE 13. View of Hiroshima, showing the destruction resulting from the atomic bomb dropped Aug. 6th, 1945.



(The Director, Geological Survey Museum.)

PLATE 14. World distribution of radium-uranium deposits. The chief productive localities are in heavy type.



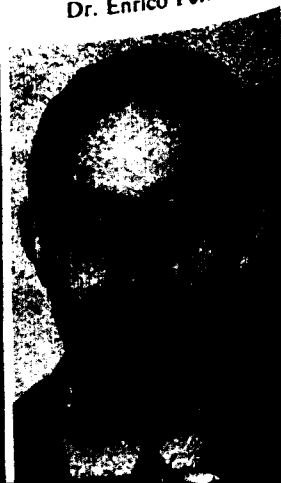
### THE MEN WHO SPLIT THE ATOM

PLATE 15. Left to right :—Dr. E. S. Walton, Lord Rutherford and Dr. J. D. Cockcroft, who split the atom at Cavendish Laboratory, Cambridge, in 1932.

Professor  
Niels Bohr

Professor  
Sir James Chadwick

Dr. Enrico Fermi



### THE TAMING OF ATOMIC POWER

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If we are somewhat impatient and wish to raise the neutron level more rapidly we could increase  $k$  slightly above 1. The neutron intensity will then double itself for each interval of time given by the formula

$$T = 0.7 \frac{\tau}{k-1}$$

Here  $\tau$  is the average lifetime of one generation of neutrons. Once the desired level is reached,  $k$  could be reduced to 1 again so that this level is maintained.

If all the neutrons were emitted instantaneously upon fission so that the reproduction time was just the time between emission and absorption, then for the example we have been considering the value of  $\tau$  would be about  $10^{-8}$  seconds. In order to bring the doubling time to a reasonable value, say 10 seconds, and so allow some time for the adjustment of the control mechanisms, it would be necessary to adjust the value of  $k-1$  to within  $10^{-8}$ . In practice this would be virtually impossible to achieve, because expansions due to slight temperature changes would alter the value of the reproduction factor by amounts much greater than this. There would always be the danger that a slight temperature change or a slight mechanical disturbance would cause the neutron intensity to rise at an uncontrollable rate.

**THE DELAYED NEUTRONS.** Fortunately, there is a delay before some of the neutrons are emitted. The delayed neutron emission is due to the fact that some of the fission products are transformed by beta particle emission into nuclei which in turn emit neutrons. The delay in the emission of the neutrons is due to the time for the beta disintegration which precedes it. Because of the delayed neutrons, the average reproduction time is increased, and the adjustment of the neutron intensity is made less sensitive

to the value of the reproduction factor. About 1% of the neutrons which are emitted in fission are delayed by an average time of about 10 seconds. If the total  $k$  exceeds 1 by less than 0.01 the prompt neutrons have a reproduction factor less than 1 and so cannot, of themselves, cause a divergent increase of the neutron intensity. Each generation of neutrons has to wait for the delayed neutron emission before a net gain in the neutron intensity can be accomplished. If we call  $k_p$  the reproduction factor due to the prompt neutrons alone, and  $k$  the overall reproduction factor, then when  $k_p$  is less than 1 the doubling time is given approximately by

$$T = 0.7 \frac{1 - k_p}{k - 1} \tau_d$$

where  $\tau_d$  is the average time for the emission of delayed neutrons (about 10 seconds). Now we may adjust  $k$  to 1.005 and then since  $k_p$  will be about 0.995, the doubling time will be about 7 seconds. It can thus be seen that  $k$  can be adjusted through the range between 1 and 1.005 and the reaction will still be quite controllable. This is a much larger range than could occur owing to normal temperature fluctuations, or other chance movements of parts of the reacting system. Because of the delayed neutrons, it becomes easy to control the chain reaction at any desired level of power output by a simple adjustment of a control rod, which may be a small part of the reacting mass. So smooth and so delicate can the control of the chain reactor be made, that by a simple motion of a light mechanism the power level can be held within a very small fraction of one per cent over long periods of time. There are very few machines which can equal this performance.

**SLOW NEUTRON REACTION.** Natural uranium contains 140 times as much of the heavy isotope U238 as of

the light isotope U235. The capture process in U238 which leads to the production of Pu239 is so large in the natural mixture of these isotopes, that the reproduction factor in a large mass of uranium metal cannot be made greater than 1, and a power-producing reaction is not possible. As has been pointed out, this difficulty can be and has been circumvented by isotope separation, whereby the amount of heavy isotope can be sufficiently reduced while the more readily fissionable light isotope is increased in concentration. However, the isotope separation process is expensive, and if all the active material which we used in our reactors were made in this way only a small fraction of the available uranium supply would be utilized.

However, natural uranium can be used to make a chain reaction, provided that the neutrons are slowed down in the reactor. Such a reactor is called a slow neutron reactor in contrast to the fast neutron reactor we have been discussing up to now. When they are moving slowly enough the neutrons absorbed by natural uranium cause fission more frequently than they produce U239. The crucial quantity for a chain reaction is the number of neutrons produced per neutron absorbed. For natural uranium this number becomes greater than 1 when the neutrons are moving slowly enough, hence a chain reaction is possible. When the neutrons are moving more rapidly, this number is generally less than 1, and a chain reaction is not possible.

The slow neutron reaction was in fact successfully made with natural uranium several years before the isotope separation plants could produce sufficient amounts of uranium enriched in the U235 content to establish the fast neutron reactor.

There is, however, one catch. The neutrons which are emitted in fission are fast neutrons. Their velocity is of the order of  $10^9$  centimetres per second. In order to establish a slow neutron chain reaction it is necessary to reduce the

velocity of the neutrons to about  $2.5 \times 10^5$  centimetres per second. This is the average velocity of neutrons which are moving owing to the thermal agitation produced by a temperature of  $20^\circ \text{C}$ . The process whereby neutrons may be slowed down was discovered by Fermi in 1935. He found that placed in a medium containing light elements, the neutrons would make elastic collisions with these light nuclei and with each collision some of the energy of the neutron would be transferred to the nucleus with which it collided. The process of slowing down neutrons has been given the name moderation, and the material in which this process takes place is called the moderator.

The slowing-down process does not continue indefinitely because the moderating atoms are themselves in motion owing to their thermal agitation. When the neutrons are slowed down to thermal energies they gain energy by collisions just as often as they lose it, so that on the average their energy becomes equal to the thermal agitation energy of the moderator. At these low energies, fission in the heavy isotope does not take place at all, but it happens that the rate of fission of the light isotope is greatly increased, much more than the competitive capture process in the heavy isotope. Hence the neutron production for each neutron absorbed by both isotopes in the natural mixture is sufficiently greater than 1 for a chain reaction to become feasible.

We have now introduced a new substance into our reactor and we have to take care that the neutrons are not absorbed in the moderator to such an extent that the reproduction factor falls below 1.

**RESONANCE CAPTURE.** Care must be taken that while they are being slowed down an excessive number of the neutrons are not captured by the heavy isotope. The probability that a neutron will be absorbed and produce

fission in the light isotope, and the probability that it will be captured in the heavy isotope, both vary considerably according to the velocity of the neutron. In general, when the neutron is moving much faster than the thermal agitation velocity, the ratio of fissions in U235 to capture in U238 favours capture. In particular, there are certain ranges of neutron speeds in which the capture in U238 becomes enormous. These are called the resonance bands, and it is particularly important to minimize the amount of resonance capture if we are to keep the reproduction factor above 1.

The amount of resonance capture can be made small if we can slow the neutrons rapidly enough for them to spend only a small fraction of their time at the dangerous speeds. An ingenious scheme which was used in all the chain reactors using natural uranium was to arrange the uranium in lumps in the moderator in some sort of lattice array. Such an arrangement has the distinct advantage over a homogeneous mixture of uranium and moderator that a large fraction of the neutrons which are being slowed down in the moderator may pass through the resonance region without coming in contact with the uranium at all. Saying the same thing in other words, once the neutrons reach the energy region where they could be strongly absorbed by the resonance capture process they have a good chance to make another collision with a moderator nucleus before reaching the uranium, and so to escape the resonance trap.

Once the neutrons reach thermal energies the lattice arrangement is a disadvantage, because now we want the neutrons to be absorbed in the uranium and there is the danger that they will be absorbed in the moderator before they reach the uranium. However, by carefully proportioning the size and the spacing of the uranium lumps in the moderator the resonance trap can be made small enough, without too much loss from absorption by the moderator.

**MODERATORS FOR NEUTRONS.** Hydrogen, or more practically, in order to obtain a high density of hydrogen nuclei, hydrogenous substances like paraffin or water, slow down neutrons more rapidly than does any other substance. By a head-on collision with the hydrogen nucleus, which has the same mass as the neutron, the neutron can lose all its energy at once and be stopped completely. Most of the collisions, are, however, more or less glancing, so that on the average the neutron will lose half its energy in a single collision. Hydrogenous moderators offer the best opportunity for keeping the resonance trap small, but unfortunately hydrogen captures slow neutrons fairly readily. The amounts of hydrogen which would be required to make the resonance trap small enough would absorb too many of the neutrons once they reached thermal energies. It does not seem possible to make a design with natural uranium and water in which the reproduction factor is greater than 1.

The next most desirable moderator is deuterium in the form of heavy water. Deuterium is the heavy isotope of hydrogen and is made by isotope separation. For this reason it is a fairly expensive substance. The capture of neutrons is much less in heavy water than it is in ordinary water. Heavy water has been successfully employed as a moderator, with natural uranium, in the chain reactor which was built at the Argonne Laboratory in Chicago.

Helium, though it has a low capture, is not available in a sufficiently dense form to be practical. Lithium and boron, the next lightest elements, capture very strongly. Beryllium could be used, but it is still a fairly costly metal. Carbon in the form of graphite, while it cannot provide as high a reproduction factor as heavy water, has the advantage of being relatively cheap and abundant, and for this reason has been used in most of the natural uranium reactors which have been built to date.

**REPRODUCTION FACTOR IN THE SLOW NEUTRON REACTOR.** The reproduction factor in the slow neutron reactor can be expressed in a simple formula. Some of the neutrons in emerging from the uranium lump produce fissions in both U238 and U235 while their energy is still high. We denote by  $E$  the multiplication of neutrons by this process, by  $p$  the fraction of neutrons which escape the resonance trap, by  $f$  the fraction which are absorbed by uranium once thermal energies are reached, by  $N$  the number of neutrons produced for each neutron absorbed by uranium, and by  $L$  the fraction of neutrons which are lost by leakage. Since  $(1-L)$  is the fraction of neutrons *not* lost by leakage, the reproduction factor is given by the formula,

$$k = EpfN(1-L)$$

**LEAKAGE: REFLECTORS AND SHIELDS.** The loss of neutrons by leakage can always be made as small as desired by making the reacting system sufficiently large. In the natural uranium reactor it is necessary to keep the loss of neutrons by leakage down to a few per cent. This requires a very large assembly. In a certain measure the leakage of neutrons can also be reduced by surrounding the active material with a reflector. A large fraction of the neutrons which leave the reacting structure enter the reflector, make collisions with the nuclei there, and in this way are turned about to re-enter the reactor. By the use of a reflector the amount of active material required to achieve criticality may be appreciably reduced.

In the slow neutron reactors graphite has been used as a reflector so as to reduce the amount of uranium needed to reach criticality.

The reflector serves another important practical purpose. It reduces the number of neutrons and gamma rays which are emitted from the reacting structure. Both the neutrons

and the gamma rays are dangerous to man and special care must be taken to reduce their number below the tolerable amount.

**CONTROL OF THE SLOW NEUTRON REACTOR.** One way to control the reactivity of a reactor has already been indicated. It can be done by changing the neutron leakage by moving one part of the reactor relative to another. But there is another possibility where slow neutrons are concerned. Certain substances, especially boron and cadmium, capture thermal neutrons very strongly, and it has been found convenient to use rods or strips of these materials which can be moved in or out of the reactor to change the reactivity. Such control rods alter the reproduction factor by absorption of neutrons rather than by altering the loss of neutrons by leakage. The control is effected by the adjustment of a light and easily movable mechanism.

In the slow neutron reactor the reproduction time even for the prompt neutrons is much longer than in the fast reactor. The thermal neutron travels at a much lower velocity (2500 metres per second) and travels a much greater distance (perhaps 3 metres) before it is captured, so that the reproduction time for the prompt neutrons is about a thousandth of a second. For this reason the energy production in the slow neutron reactor can hardly be rapid enough for an explosion to take place. In the worst case the uranium would melt, possibly even vaporize to some extent; the reaction would then stop before the pressure developed was high enough to cause an explosion. A bad fire might result and the radioactive fission products, some of which are gaseous, might escape, but if the whole were confined to a suitably designed concrete building, the disaster could be kept fairly well localized.

**THE CHAIN REACTING MACHINE.** The first chain

reactor used natural uranium with graphite as the moderator. It was built at the University of Chicago and completed in December 1942. Since the mass production of uranium metal was only beginning at that time, most of the structure was made up of humps of uranium oxide and only a small amount of metal (about 6 tons) was used. Since the number of neutrons emitted when one neutron of thermal energy is absorbed by natural uranium, is not very much above 1, close attention had to be paid to all losses of neutrons. In particular, impurities present in either the uranium or the graphite might absorb an excessive number of neutrons. The first experimental lattice structure which was erected to measure the reproduction factor was built at Columbia University in July 1941, using commercial grades of uranium oxide and graphite. This gave a reproduction factor of only 0.87, largely because of the impurities in the materials used. The major industrial problem which had to be solved, before a successful chain reactor could be made, was the production of very specially pure substances. Some elements were not tolerable if present to the extent of one part per million. To produce sufficiently pure materials was the primary task of the Metallurgical Laboratory in Chicago, which was organized in February 1942, and the successful production of the first chain reaction in December of the same year was testimony that this task had been completed.

The first chain reactor had no provision for cooling and was operated at a power output which did not exceed 200 watts. In the following year the Clinton Pile, a lattice structure using uranium metal and graphite, was constructed at Oak Ridge, Tennessee. The metal was in the form of short cylindrical slugs and was placed in long channels in the graphite so that air could be made to flow past to remove the fairly large amount of heat which was developed in them. To protect the hot metal from oxi-

dation by the air, the uranium slugs were enclosed in gas-tight aluminium cans. By June 1944 the power output exceeded 1800 kilowatts.

A number of much more powerful plants were built at Hanford, Washington. These were also lattice structures of uranium metal and graphite, but were water-cooled this time in order to remove very large amounts of power.

**PRODUCTION OF PLUTONIUM.** These high-power piles were not designed for power production. Rather, the heat production which was necessarily associated with the operation of the plants was a nuisance, since it had to be disposed of in some way. Nor were they to manufacture fission products: the emphasis was on capture, not fission. The plants were built in order to produce plutonium, the substance which is made from the capture of neutrons in U238, because plutonium was found to be a highly fissionable substance and very suitable for making atomic bombs. The resonance trap, which we had to struggle against so much in order to make a chain reaction go at all, was just what is needed in plutonium production. An elementary consideration shows roughly how much energy must be dissipated because of the energy released on fission, in order to produce a pound of plutonium per day. Somewhat more than 1 neutron per fission is needed to sustain the chain reaction, and to provide for the leakage and the absorption by the moderator and impurities; all the remaining neutrons which are emitted per fission can be captured by the U238 for the plutonium production. Thus, approximately 1 plutonium atom will be made for each fission and the energy dissipation will have to be ten million kilowatt hours per pound. On a 24-hour schedule, the plant would have to operate at a power of a quarter of a million kilowatts, to produce a pound of plutonium per

day. The removal of this amount of power, which is sufficient to heat a city, is an engineering problem of inspiring proportions and makes up a large part of the cost of the plant.

In addition to the heat removal, the problem of chemically extracting the newly-formed plutonium from the uranium and the fission products is of comparable magnitude, and perhaps of even greater difficulty. The fragments which are produced by the fission are intensely radioactive. The fission does not always take place in exactly the same way, and the fragments which are produced are not always the same ones, but differ somewhat in mass and charge. Only rarely does the splitting give two equal fragments. To become stable the fragment has to emit several beta particles in succession. The original fragment may emit the first beta particle in a very short time, but the later beta particles may be emitted after an average time of weeks, months, and in a few cases, many years. Accompanying the emission of beta particles is the emission of gamma rays, and these radiations, since they can disrupt cells and tissue, are dangerous to life. This means that the handling and chemical processing of the uranium slugs which contain both the fission products and the plutonium must be done behind shields and by remote control in order to protect the men. Furthermore, since the radiations can disrupt chemical compounds, the problem of carrying through the sequence of chemical reactions required for purifying the material needs special consideration. In practice, in order to reduce the intensity of the radiations from the fission products, a certain time is allowed for "cooling". The pile is shut down and the active uranium slugs are pushed into a storage basin. After a month or two the activity of the slug has decayed sufficiently for the processing to be carried out.

The Clinton Pile was constructed in order to produce

plutonium on a pilot plant scale, so that the separation problem could be studied.

**DANGERS FROM RADIATION.** A nuclear reaction operating at a power output of 1 watt produces as many gamma rays as 3 grams of radium. About half as many neutrons are emitted but the neutrons are from 5 to 10 times as dangerous. However, a large fraction of both the neutrons and the gamma rays are absorbed in the reactor so that only from 1 to 10% of them actually emerge, depending on the design of the reactor. As a rough figure we may take the radiation from a one-watt reactor as equivalent to that from 1 gram of radium, but keep in mind that any shielding which is provided must be against neutrons as well as against gamma rays.

The unit of radiation dosage is the Röntgen, or briefly the R unit. It is the amount of radiation which can produce 1 electrostatic unit of ionization in one cubic centimetre of air. The tolerable dose for gamma radiation is taken to be 0.1 R per day, while 500 R taken in a short time is considered fatal, and radiations of this order killed a very large number of persons when the atomic bomb was used over Hiroshima and Nagasaki. If we assume that a man may want to stay about 10 feet away from a one watt nuclear reactor for 8 hours a day he will receive about five times the tolerable dose. In plants which operate between 10,000 kw\* and 100,000 kw a shielding factor of from  $5 \times 10^7$  to  $5 \times 10^8$  is required. For neutron and gamma ray shielding, each foot of concrete will afford a reduction in both the gamma rays and the neutrons by a factor of 10, so that for adequate protection of personnel a concrete shield between 8 and 9 feet thick is required. Considering that a reactor even if made of pure fissionable material can hardly be smaller than 3 feet on a side if it is to dissipate 100,000 kw

\*1 kw=1,000 watts.

(this large amount of energy appearing as *heat*), it can be seen that the weight of the shield above (at 150 lb/cubic foot) will be about 600 tons.

By using shields having higher density it would be possible to reduce somewhat the total weight of the shield. Since it is necessary to provide shielding against neutrons it is not sufficient to use a heavy metal like lead alone. Some amount of hydrogenous material is needed to slow down the neutrons to an energy where they will be readily captured, so that even if we are fairly clever about the design of the shield it is clear that the total weight of our reactor must be of the order of 100 tons.

One major consideration in the design of a power reactor is that practically every substance which is inserted becomes radioactive from the capture of neutrons. For this reason any part which may require some maintenance should either be protected from neutron irradiation by a suitable shield, or some means be provided for it to be reached and manipulated from behind a shield, or with remote-control devices.

**APPLICATION OF NUCLEAR POWER.** If the nuclear reactor must weigh of the order of 100 tons—and for inexpensive shielding, a good deal more—it is clear that we cannot hope to see motor-cars driven with this type of power. A 200-ton airplane, driven by a nuclear power plant, becomes a possibility, and it is true that such planes of this size are being contemplated.

For ocean-going vessels and submarines the nuclear reactor is particularly well suited, because not only can it supply a large amount of power but it need not be refuelled very frequently. Another practical use of such nuclear reactors would be for stationary power plants in remote places where coal or water power are not readily available. The nuclear reactor also opens up the possibility of an

interplanetary space ship on the rocket principle, if not manned, at least with remote control by radio.

**NATURAL URANIUM REACTOR.** In our discussion so far we have indicated two general types of nuclear reactors, slow neutron reactors and fast neutron reactors. Natural uranium can be and has been used in the slow-neutron type with a number of different kinds of moderators, but care must be taken not to introduce neutron-absorbing substances in the cooling arrangements in excessive amounts. Moreover, the size of these units must be made quite large in order to reduce the loss by leakage, although this is not always a disadvantage if large amounts of power are to be removed. The total weight of such an installation may be several thousand tons including shielding, but the power output may amount to 1 million kilowatts or more.

Such a reactor initially "burns" only the light isotope U235, which is present only to the amount of 0.7% in natural uranium, but as we have seen, the fissionable element Pu239 is produced simultaneously from the more abundant heavy isotope U238. Insofar as the number of neutrons per fission is greater than 2 it should be possible so to arrange the design that somewhat more than half of these neutrons are used to maintain the reaction, and the remainder to produce Pu239 to replace the U235 which is being burned.

Under such conditions when the U235 is all gone the reaction could continue on the Pu239 which was made to replace it, and in this way most of the uranium could be utilized.

In the course of the reaction, fission-products are formed. Some of these products may absorb neutrons so strongly that after some time, the excess neutrons will be used up by absorption in them and the reaction will stop. In this case it will be necessary to tear down the reactor, chemically

remove the fission products, and refabricate uranium metal with the appropriate amount of the plutonium added to make the material sufficiently reactive. The fission products being intensely radioactive, all this procedure requires elaborate plant, and equipment with remote-controlled apparatus to handle the intensely radioactive material behind thick shields.

One limitation to the power-output and life of any nuclear reactor is the effect of the strongly ionizing particles and rays on the structural properties of the materials from which the reactor is built. Owing to their strongly ionizing effect, the gamma rays, the neutrons, and the fission fragments themselves destroy the molecular bonds of a large number of molecules. A large number of potentially useful substances will not be usable for this reason. The substances which can be used are those which tend to return to their original state even after intense ionization. For the most part these substances are the elementary metals and simple ionic compounds. The extent to which even these will withstand the higher and higher irradiations which will accompany the attempt to extract greater and greater power outputs is not at present known.

**REACTORS WITH CONCENTRATED FISSIONABLE SUBSTANCES.** Material enriched in U235 can be made by isotope separation, while, as we have seen, Pu239 can be made in the slow neutron natural uranium reactor. By concentrating the amount of material which is fissionable by slow neutrons, the number of neutrons produced per neutron absorbed in the active substance may be increased, a higher leakage may be tolerated and the size of the reactor reduced. The neutrons which escape by leakage need not be lost completely, since we may surround our reactor with natural uranium so that the leakage neutrons will be utilized in the production of Pu239.

As a general thesis the neutrons are too precious to waste at any time, and it is usually possible to arrange for them to be usefully consumed. In many cases the neutrons may be used to produce special radioactive materials. Some fission products are useful radioactive materials very much worth while recovering.

With sufficiently enriched material a fast neutron chain reaction becomes possible. Whether a fast neutron reactor has special advantages for power production over the slow neutron reactor cannot be clear in this early stage of the development. There are differences which may prove advantageous in some applications and not in others. The moderator and its accompanying absorption is eliminated, a definite advantage. The poisoning due to fission products will be different—perhaps less great. On the other hand, a larger amount of active material is required in the fast neutron reactor because at the higher energies the neutrons are less readily absorbed, and therefore more likely to escape.

**SAFETY IN THE NUCLEAR REACTOR.** It is not easy to imagine that a nuclear reactor which has been designed for power production could explode by accident in the way that the atomic bomb explodes. In order to get such an explosion, as we saw earlier a special set of conditions are required which have to be prepared for specially in the mechanical design. The active material has to be assembled to give a very large reproduction factor in a very short time. The great danger in the nuclear reactor is that it is a great store of intensely radioactive fission products. In a high-power reactor the radiations from these fission products might be equivalent to many tons of radium. If these fission products were to escape, the risk to the health or life of all persons within some miles of the plant would be great.

The usual design of a reactor includes a number of safety rods. These rods usually act by absorbing neutrons and so decreasing the reproduction factor, in the event of the operating level or concentration of neutrons exceeding a certain predetermined value. These are usually adequate to prevent damage from most of the possible mishaps, but since they are mechanical devices they take at least a second or so to act. For an accident which increases the reproduction factor 1% into the region where the prompt neutrons can multiply of themselves, an enormous intensity could be reached before the safety rods would have a chance to act. If the safety rods did not act the reaction would stop itself by some sort of mechanical displacement which would cause an increase in the neutron leakage. This might be just a thermal expansion of the active material, or it might wait for the metal to melt or to vaporize. In the extreme case, the accidental increase in the reproduction factor might be so large that a low order explosion would occur before the vaporized active material had a chance to move very far. In most of these cases the reactor might be wrecked and it would be difficult to repair it because of the intense radiations from the fission products; but the greatest worry comes from the possibility that, in the course of the vaporization due to the explosion, the fission products might be let loose among the neighbouring population.

Generally, most of the dangerous contingencies can be rendered impossible in the design, but it is necessary to examine the possible kinds of accidents very carefully in every case. In a safe design, less active material is used than can possibly give an excessive reproduction rate in any of the conceivable arrangements of the material. Nor should it be possible to bring any additional material sufficiently near for the reproduction factor to be increased; shielding permanently placed about the structure can

prevent this. The reactor should be designed to be temperature-stable, so that an increase in temperature reduces the reproduction factor. Moreover, loss of coolant should decrease the reproduction factor, or if this is not possible the loss must not be so fast that the safety rods cannot act in time.

**UTILIZING THE POWER.** None of the nuclear reactors which have been built to date have been designed for power use. For this reason much experimental work has yet to be done in order to explore the possibilities of this source of power. Although the energy appears initially as motion of the fission particles this motion is quickly dissipated to the surrounding material and appears as heat. If the purpose of the nuclear reactor is to supply heat—as for the heating of cities—it is not particularly difficult to transfer the energy by passing cold water through the reactor, so turning it to hot water or steam. If we are interested in some form of mechanical or electrical power the heating of water would not be a very efficient use of the nuclear power. Other cooling media which could extract heat at much higher temperatures would be more desirable, although each possibility has to be judged from the point of view of neutron absorption, radioactivity, stability against radiation and corrosion. Liquid bismuth and liquid sodium are possible coolants in this class. Nor should gaseous coolants be excluded, for it is quite conceivable that a nuclear reactor might serve as the heat source of a jet type engine.

## THE PHYSICS OF THE BOMB

*By P. Morrison*

**NUCLEAR ENERGY CONTROLLED: THE PILE.** The Hiroshima explosion signalled to the world that the large-scale release of nuclear energy had been achieved. The spectacular and terrible detonation drew all attention to the catastrophic release of energy which in the bomb had been made possible. Even now that the facts of the matter are known, a belief remains that the "control" of nuclear energy is still beyond our means. Nothing could be further from the truth. As the reader of the article by H. L. Anderson, p. 63, will remember, the nuclear chain reaction has operated literally every day from December 2, 1942, until now. It has worked in one of the several existing forms of piles, or chain reactors, whether the uncooled pile of graphite blocks and  $\text{UO}_2$  lumps which was man's first nuclear reactor, or the huge plutonium-producing units at Hanford which quietly warm the Columbia River. This is operated with a small reproduction factor so that the number of neutrons produced in a generation of the chain by a single neutron reaches unity *only* after the delayed neutron emission from the fission fragments has occurred. By this means the chain reactor is made into a smooth and trouble-free device. Probably no other machine can be made to operate successfully over such a great range of intensity, and stabilized at any operating power level allowed by the engineering design by the simple motion of a single control element. No complicated moving mechanism or delicate vacuum system forms part of a chain reactor. The steadiness and smoothness are noteworthy; the system is inherently stable. And why not, for the only moving parts are neutrons! At both

the Argonne and the Clinton piles, one minor problem has been to provide a routine of meter-reading and recording exacting enough to ensure that the man who is operating the pile does not find it too easy to fall asleep. The normal demands of keeping the pile intensity constant are so easily met that the operator has very little to do. Starting and stopping the reactor is simply a matter of displacing the control rods by a predetermined amount.

The problem before the whole Manhattan Project, given the production of quantities of fissionable material, was to make the chain reaction uncontrolled and explosive. The Los Alamos laboratory was given this problem, and its practical solution was in almost every detail conceived and executed there. While the scale of the operations at Los Alamos is far smaller than that at the great production plants, the diversity and the difficulty of the research and production there carried out make the site a unique and incredible one. Military security regulations still prohibit the discussion of many of the interesting problems there solved, but following the Smyth report and making obvious extensions of previous knowledge very much of the physics of the bomb can be discussed.

**THE MEANING OF A MICROSECOND.** It was clear from the beginning that the great piles of uranium and moderator could not make satisfactory military weapons. In the first place, they were too large for reasonable means of transport. Even more so, while they are capable of running at any power, and can certainly be so set that the intensity will melt any structure, they cannot violently explode. The rapid rate of energy release is what makes an explosion. In the pile, the balance of neutrons made in the chain against those lost by non-fission capture is too narrow. The gain in number of fissions per generation is small, so that many generations are needed to produce a doubling of

the intensity. Even more important, the chain operates on thermal neutrons. Such neutrons move at rifle-bullet speeds, and in travelling the many feet that are required to escape from the pile, they make a large number of collisions and eventually spend a lifetime of a thousandth of a second or so in each generation. Since many generations are needed, the time which would be required for the explosion of a pile may be measured in hundredths of a second. A block-buster explodes in the time it takes for a detonation wave, travelling some five thousand metres per second, to cross the mass. This time is perhaps one hundred microseconds.\* The deliberate explosion of a pile would have the character not of a bomb, but perhaps of a steam boiler bursting.

All the criteria for a weapon are satisfied by a very different kind of chain reactor, the kind from which an atomic bomb is actually made. The reactor is not a large and carefully arranged lattice of moderator and natural uranium, but a small compact mass of nearly pure fissionable material. Instead of the tons of even the best pile, the critical mass of a sphere of pure plutonium or highly-enriched U235 is measured in kilograms. The loss of neutrons to the chain by non-fission capture is nearly zero, so that the reproduction factor is large, much greater than the near-unity value of the pile. Perhaps most important, the chain no longer operates on thermal neutrons. Even the primary fission neutrons have a good chance of producing daughters for the chain. Only a few collisions make up the whole life-history of even an unusually long-lived neutron, and the fast neutrons move not at rifle-bullet velocities, but at velocities many thousands of times greater. A typical fast neutron would travel from Los

\*Throughout this article we shall find it convenient to measure time in millionths of a second, or microseconds. A high-velocity rifle bullet could cross the letter "o" in one microsecond.

Alamos to London in a second. A generation in the small chain reactor which is a bomb, is measured by the time that it takes a fast neutron to travel a few inches. The time is perhaps a hundredth of a microsecond. And the intensity increases markedly in a single generation if we use a mass well above the critical mass.

How many generations are needed for an explosion? We know that the energy released from the fission of a pound of fissionable material is about that resulting from the explosion of eight thousand tons of TNT. The present atomic bomb, which yields the energy of some twenty thousand tons of TNT, must therefore consume a couple of pounds of material. If to every fissioned atom we assign one neutron—the one that did the job—we must have released two grams of neutrons at least in the explosion. But in two grams of neutrons there are about  $10^{24}$  particles. All of these descend from a single neutron which initiates the chain. If we needed, for the sake of example, only one generation to double the intensity, this would mean about seventy-five generations of the complete chain. The whole process would take only a microsecond, and the violence of the true explosion would clearly be present. This is the very opposite of the controlled reaction of the pile. It is worth while noting that the delayed neutrons, which are not even emitted for tenths of seconds after fission, play no part whatever in the explosion of the bomb, though their role is determining in pile operation. The two applications of the nuclear chain are as different as the burning of coal and the detonation of TNT. It is not the least remarkable property of the fission chain that the same mechanism can act in two situations physically so different.

**THE CHAIN STARTS.** From all this it is perfectly clear how to make a bomb. You must bring together enough fissionable material to have more than a critical mass. The

more you assemble together, the less the proportionate leakage of neutrons out of the mass, the greater the increase of neutron intensity per generation, and the more rapid the whole process. The trick, of course, is to make the initial assembly. For the geometrical conditions and the nature of the material alone determine the rate of change of the neutron or fission intensity, and hence the energy release. There is no switch to turn the chain reaction on or off. You must do this by modifying the shape. If you have, say, two pieces of material each weighing nine-tenths of the critical mass there will be no self-sustaining chain until you begin to bring the two pieces together. As they draw close the neutrons which once escaped out of the neighbouring surfaces of the two pieces now have some chance to take part in the chain, because they are captured and induce fissions in the other piece of material. Long before you had caused the two pieces to make contact, the total configuration would have become critical. As the pieces approached even closer the reproduction factor would steadily increase, and the neutron intensity, had a chain started, would grow at an ever-increasing rate. If your actions were slow, the energy released would have melted the pieces long before they had approached contact. Under these circumstances the energy released would not be that of thousands of tons of TNT, but simply that sufficient to melt or otherwise destroy the assembling mechanism. Obviously this will not do. The solution is clear: bring the pieces together rapidly. Assemble them by making one piece the projectile of a small cannon, the other its target, placed directly at the mouth of the cannon. But recall the time scale of the whole phenomenon. Only microseconds are required for a tremendous energy release. Even special artillery will not move our pieces more than a fraction of an inch in this time. It is clear that the movement needed must be of the order of the size of the masses assembled, certainly several

inches. There is only one way out of this dilemma. Nothing will happen to our assembling device if the chain does not start until the pieces are assembled.

Let us try to follow in words the incredibly rapid events which make up the nuclear explosion, beginning with the role of chance and ending with the catastrophe that follows.

**THE TOSS OF A COIN.** All the spectacular effects of the atomic detonation are started by an event as purely chance in its nature as the toss of a coin or the flip of the ball in roulette: the presence of a single neutron. If the neutron appears, by sheer chance, before the assembly has reached the degree of supercriticality which its designers had hoped for, the bomb will fail, though all of its components function exactly as planned. For the first time, perhaps, a single atomic event, a necessarily uncontrolled circumstance, can measurably affect the world of men. Again, if no neutron appeared, though some were expected, the projectile might pass through the target, and the bomb parts fly apart again without detonation. Of course, some ingenious though simple device can be introduced to prevent the fiasco of failing to get started on the chain, the fiasco of post-detonation. Any neutron source—such as a beam of radium alpha-particles arranged to strike a beryllium foil when the position of target and projectile is the best possible one—which can be turned on at the right time, will make it very sure that a neutron is present, by emitting many of them in the time the projectile moves only a short distance. But nothing can save the bomb from *pre*-detonation except chance.

However he may be intrigued by the philosophic implications of the predetonation problem, the designer of the atomic "gun" must face it realistically, which is to say quantitatively. While he cannot escape pure chance, he may estimate how likely is his failure. He will not worry if

after he has finished his design he is willing to wager odds of 100 to 1 that his gun will explode. No military venture has a chance of success much greater than that, neutrons or not. Is this high reliability possible? Let us make a guess at the numbers, using only pre-war information, and not the precise data now available to the workers of the Manhattan District. You will remember that the critical mass of U235 is measured in kilograms. Such a mass—even if we are pessimistic and take Dr. Smyth's upper limit of one hundred kilograms—will be only about six inches in diameter. The projectile and the target will each be of this size in a possible design. Now when these two active pieces are within say six inches of each other, the neutrons from each piece will find their way with considerable probability to the other. The assembly will be supercritical. If the chain begins, it will build up to a high enough number to destroy the whole device in a few microseconds, as we saw above. The stray neutrons must be kept down. How well must this be done? The projectile in a light naval gun moves six inches in a fraction of a thousandth of a second (a long time in our nuclear scale, some three hundred microseconds). During this time, we should have no neutrons, or at least none to start the chain. It is clear that not all neutrons will start the chain. Some will be absorbed in the steel structure of our gun, some may even produce a fission, but the neutrons from the fission fail to find the active material again to continue the chain. About the average neutron we can make the sure prediction that it will begin a divergent chain reaction in a supercritical mass; but about a single neutron we must quote only probabilities. But we will leave this out of account, so as to plan for the most difficult case. We shall assume that any neutron appearing in this crucial third of a millisecond can make the bomb fizzle out. We must then require that during that time the wager is a hundred to one against any neutron appearing.

Since the neutrons may come at any time taken at random, this is about equivalent to saying that in thirty milliseconds on the average not more than one or two neutrons appear. Where will neutrons come from? The Smyth report lists the sources: (i) cosmic rays, (ii) nuclear reactions in light impurities in the heavy metal, in which the weak alpha rays of uranium may induce neutron emission (analogous to the familiar radium-beryllium neutron-producing reaction), (iii) the release of neutrons by the spontaneous fission of the uranium itself. Let us estimate these stray neutrons. Cosmic rays produce a neutron at the rate of a dozen or so per square foot per second. The impurities, it can be shown by simple calculation, cannot produce even this many if the metal is quite reasonably pure. The spontaneous fission rate is publicly known for normal uranium through work published in 1940 in the *Physical Review* (the chief American physics journal) by two Russian workers, who first observed this queer phenomenon and there described it. Just as uranium spontaneously disintegrates by alpha-particle emission, it spontaneously disintegrates, though very rarely, by fission, without any incoming neutron to cause the event. The rate of such disintegrations is very slow. For every uranium atom which dies by spontaneous fission, tens of millions die by the emission of an alpha particle. The Russian work of 1940 indicates that between five and fifty neutrons will be given off spontaneously by a kilogram of normal uranium in one second. This rare event—so slow and improbable that it would take uranium from ten to a hundred million times the age of the earth to decay by this process alone—is the controlling factor in our problem. We do not know how this rate varies from isotope to isotope; let us assume it is the same for U235 as for U238. Then spontaneous fission will produce some five thousand neutrons per second in our bomb, and is by far the chief source of stray neutrons. Our design cannot get the

reliability we had hoped. Even if we take some advantage of the fact that every neutron will not start a chain, the chance of pre-detonation by a neutron appearing in the crucial three hundred microseconds is something like even, and not a hundred to one. We have been too pessimistic, of course. For some of the six inches of motion is near the fully assembled position and here the predetonation will make very little difference to the final energy release. The problem is after all one of continuous gradation from dud to great explosion, and we have spoken as though it were all or none. But our numbers, guesswork as they are, still show that the controlling factor in bomb design may very well be predetonation.

Against this danger there are few measures the designer can take. He can reduce the cosmic ray and impurity neutrons by shielding and by painstaking purification. But their importance is not great. He cannot affect the spontaneous fission rate. To reduce the probability of predetonation he may reduce the amount of material in the bomb. When he does this, of course, he reduces the potential energy release. He must use at least a reasonably supercritical total mass. The spontaneous fission rate of the particular isotope which is his active material will thus help determine the size of his bomb: it cannot be too small, or it will not be sufficiently supercritical, nor can it be too large, or the spontaneous fission may cause pre-detonation. Only one thing is at his choice. As the Smyth report says, he may "reduce the time of assembly to a minimum". He may shoot the two parts together at great speed. In this way he can cut the chance of a fizzle just in proportion to the amount by which he reduces the time of assembly. The atomic bomb is simple, but its design is not easy!

**THE CHAIN IS UNDER WAY.** Let us trace the explosion still further. By chance and design, let us get projectile

fully meshed with target. A neutron initiates the chain reaction. For illustration (we do not know the real numbers) let us assume as we did before that a single neutron may be absorbed, and the resulting fission yields two to take its place. These two each give rise to two, and the chain is under way. In some seventy generations, one neutron has multiplied to a thousand million billion ( $10^{21}$ ) and enough energy has been released to turn the materials of our bomb into vapour. This is still no nuclear explosion. Only an energy equivalent to that of some ten tons of TNT has been liberated. Everything now depends on the next generations.

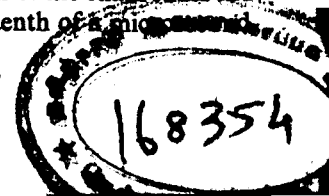
If the reaction stops now, the atomic bomb is nothing but a costly and unreliable block buster. But if after seventy successful generations, only ten more can be sustained, the chain will yield the twenty-thousand-ton explosion which devastated Hiroshima. Time is indeed of the essence. As we have said before, the fast neutrons which carry the chain in the bomb require very little time to multiply. The whole of the first seventy generations can take place in about one microsecond, during which a bullet would travel hardly a tenth of an inch, or an explosion in TNT proceed a quarter of an inch further into the mass. And the next tenth of a microsecond will make all the difference between an atomic bomb and an ordinary one.

**THE CHAIN REACTION STOPS.** The nuclear properties of matter are not affected even under the conditions now existing within the bomb. The chain proceeds as usual. It will stop only by exhausting all the fissionable material—in a perfectly efficient bomb, this is the mechanism of the end of the reaction—or by some geometrical change which will alter the supercriticality of the assembly. If the now vaporized bomb expands, its surface will increase, and the chance for a neutron to leak out of the less dense active material into the outside world will grow. When sufficient

expansion has taken place, when the chance for neutron leakage has so increased that the chain reaction no longer multiplies the number of neutrons present, the release of nuclear energy has stopped. The bomb reaction is ended. It is clear that if the bomb we have described expanded in all directions a foot or so, its density would have very much reduced. The chance that a neutron could escape from the mass without colliding with a fissionable atom on the way would have increased very much, and the excess of one neutron would probably no longer be enough to sustain the chain. To expand a foot in a tenth of a microsecond implies a motion at a speed of a few thousand miles per second, and an accelerating force corresponding to suddenly created pressures of millions of tons per square inch. It is as though the weight of ten battleships were suddenly brought to bear on every portion of a surface as big as a sixpence.

It is clear that some expansion will occur. This is in fact what limits the reaction. The details of the physics of this spectacular event will have to wait for later publication. Obviously the strength of solid materials plays no part in this phenomenon. All that matters is the behaviour of the intensely heated gases, their inertia, and the way in which the great blast wave can eat its way through the material of the bomb and the matter surrounding it, pushing out with these great pressures, until the whole device has expanded and the energy release has stopped. The release of energy in the form of the energy of motion of fission fragments, its transformation to heat, at temperatures beyond those of the centres of stars, and the expansion wave of the hot gas are all subjects of importance to the designer of bombs. For the key to the efficiency of a bomb is the speed at which this expansion takes place, compared to the speed at which the last few generations of the chain cause the energy release to multiply. The last tenth of a microsecond

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N47-2



is the crisis of the end of the reaction, just as the first three hundred microseconds were the critical time for its initiation. The measure of the difference between nuclear explosive and ordinary cordite is found in this vast change in time scale. Nuclear explosions are fast.

The role of the so-called tamper, a heavy wall of matter placed around the active component of the bomb, is now clear. Such a wall will, of course, act as a cloudy neutron mirror: it will reflect back to the fissionable material some of the neutrons which might otherwise have been lost into space. This will make a given mass of material more supercritical than without the reflector. This is obviously a sought-for result. Even on the controlled piles such neutron reflectors are used. In the bomb they are less advantageous than at first glance appears, because the time that a neutron takes to wander into the tamper and come back to the bomb again will find it arriving long after its birth. By that time the neutrons present in the bomb have multiplied considerably in number, and the inheritance of reflected neutrons from an earlier and neutron-poorer epoch is no longer so important. On the other hand, a simple mechanical property of the tamper is now of great importance. The heavy tamper must be pushed out by the expansion of the heated active material. The blast wave must move into the tamper before expansion can end the reaction. The tamper really does "tamp" the nuclear explosion, almost as the wooden tamping rod of the miner tamps the dynamite into the drill hole. It increases the pressure required for expansion, delays the final expansion, lengthens the time of the reaction, and hence increases the energy release.

**THE EXPANSION: THE BALL OF FIRE AND THE MUSHROOM.** In a fraction of a microsecond, then, the energy of the bomb has been released. From heat, part of

it has become the mechanical energy of the out-rushing material of the tamper. Some fraction of the total is in the form of "penetrating" radiation—neutrons and gamma-rays—which must be considered later. But just now the interest centres on the hot ionized star-stuff of the exploded bomb. Out the edge moves, until in a few score microseconds the whole mass occupies a sphere something like fifty feet in diameter. When the heavy uranium and steel bomb has been spread as thin as this, it no longer has the density of metal, but that of ordinary air. From this time on the expansion is slower, and the hot material mixes with the air around, by now also heated to an ionizing, beyond-white, heat. The air and the vapour of the bomb continue to mix and the heated mass eats further and further out into the undisturbed air, displacing and heating the layer beyond the edge of the hot sphere. When this hot gas has expanded until the pressure within is not greater than the pressure of the atmosphere it stops growing. Perhaps a millisecond has elapsed. The gas has formed the hot "ball of fire" which measures many hundreds of feet in diameter and glows with a white heat for as much as a second or so. It is this hot ball sitting on the desert sand which turned it into the iron-containing friable green glass that carpeted the desert floor in the test explosion called Trinity.

The ball of fire then cools a little, by radiating away its heat. In a short time it begins to rise, like the hot air balloon that it is, and the cool currents rush in around it. It rises, leaving beneath it as it goes a trailing column of dust and cloud. The great column rises, carrying within it the active fission fragments left by the burned material of the bomb. It is incredibly radioactive. For the twenty-thousand-ton-equivalent bomb has within it about a kilogram of fission fragments. The disintegration of this radioactive debris in the first few seconds or minute of its rise represents the activity of a million tons of radium!

The fission fragments, of course, are principally short-lived, and in a few hours or a day the far-spread activity has dropped by a very large factor. We who watched at Trinity could see the violet glow of heavily ionized air around the rising column as the material irradiated the upper air.

Everyone has seen the fantastic grandeur of the rising column of heated gases over the ruined cities. Two phenomena of special interest are seen in those fine photographs. The column itself is mainly a cloud, just like any thunderhead, except for the dust and vapour it holds, radioactive and generating heat. The cooler air of the upper air causes the water vapour brought up in the hot column from the air near the ground to condense and the cloud forms. As the column rises like the smoke from a chimney it may come to what is called an inversion by the meteorologists. This is a layer of air warmer, instead of cooler, than the air below it. When such a layer is reached, the gas of the column will spread out and rise no longer. This is the formation of the mushroom. But some of the gas of the column is still being warmed by radioactivity. This gas is warm enough to break through the inversion layer, and the column sends another stem from the first mushroom cap. This too mushrooms, now very high in the air, perhaps six to eight miles. All of these grand and ironically beautiful phenomena can be seen in the moving pictures of the attacks on Hiroshima and Nagasaki.

**THE SHOCK WAVE: HOW A CITY IS FLATTENED.** We have left the ground for an account of the relatively lasting spectacle of the mushroom. But a grimmer and more important phenomenon has already taken place below. A large fraction of the energy of the explosion went into pushing aside with extraordinary speed a large mass of air as the ball of fire formed. The pressure wave which pushed aside the tamper as the bomb expanded continues through

the ball of fire, and, leaving the ball of fire when the gases stop expanding rapidly, hammers against the undisturbed air with terrible force. This wave is called a shock wave. The physics of the shock wave, which differs only quantitatively in this atomic explosion from the similar wave produced by any explosion, is a subject once overlooked by physics in the main, but forged to a real completeness by the requirements of the war.

A shock wave is simply a sharp sound wave of very great intensity. In a sound wave the pressure increase, followed rapidly by an equivalent decrease, is small in magnitude. But the great compression which the push of the atomic explosion gives to the air not only increases its pressure by a very large factor, but also heats it, as a tyre is heated by rapid pumping. The sound wave so started travels faster than sound in the cool air still unreached by the shock. The shock front penetrates further and further. As it moves it represents a sharp boundary between two regions of air: one region ahead of the shock, yet untouched, still cool and at normal pressure; a second region, hot, compressed, just behind the front, where disturbances travel at high speed in the hot dense air. As the shock front moves it loses some energy by fulfilling its purpose, that is by pushing over anything in its path, but more and more its energy leaks away as heat, by conduction and radiation. The air in the very front of the atomic bomb shock is at first actually red-hot. The shock becomes increasingly less sharp; as it spreads in a great sphere the pressure excess and the temperature rapidly fall, and far away, the disturbance has faded out into an ordinary sound wave, and a rumble is the only evidence of its passage. All the phenomena of sound are associated with the shock wave: it may be reflected, it may leave shadows, it may diffract around obstacles. Such phenomena are responsible for the not quite predictable behaviour of a shock wave passing through the complex pattern of a city.

All who have seen the results of an air raid incident will fully appreciate what I mean.

The wave itself is simply a transmission of pressure through the air, successive layers in turn feeling the compression. Behind the compression there follows generally a rarefaction, representing the wake of the original displacement. After the entire wave, both the increase and the decrease of pressure, there comes a real current of air, a wind, which may in such great explosions reach hurricane velocities near the centre, especially in constricted places like buildings.

How is damage done? The high pressures of the shock hammer on the surfaces of buildings. The air inside—ahead of the shock—is, of course, still at ordinary pressures. The difference in pressure represents a force which can break the strongest walls. Through every opening the pressure difference will force a current of air as well, a wind which devastates the interior of most structures lucky enough to withstand the main force of the shock. Here a few figures will make very clear what happens.

At about a thousand feet from the atomic explosion the excess pressure in the shock is as much as ten or fifteen times the normal pressure. This is the pressure needed to cause the death of a man from blast alone, from crushing the walls of the chest and smashing his ribs. At about twelve or fifteen hundred yards the over-pressure has dropped very much indeed. The excess is here only about a third of the normal pressure already present. This seems small, but it is enough to demolish most houses, brick, wood or stone. On an ordinary wall such a pressure difference means a thrust of fifty tons, the weight of a locomotive. Still further out the over-pressure drops more and more. At two miles, it is only a mere fifteen per cent of the normal pressure. But this is as much as the effect of a tornado, and will damage structures of any ordinary kind, and demolish the

weaker ones. At three miles the effect is down to that of a strong gale, and only light roof tiles, signs, or such weak objects will suffer damage. In Hiroshima we found the first missing roof tiles and broken window panes at eight miles from the blast.

British readers will be impressed by comparable figures for the V-1 explosion: the killing over-pressure is there found only at fifty feet; the demolition pressure at seventy-five yards, and the tornado effects at two hundred yards. The explosions of the atomic bomb are by far the greatest man-made blasts ever observed.

One difference between the blast phenomena in the atomic explosion and those of a block-buster is the duration of the over-pressure, that is, the depth of the strong shock front. The shock from a block-buster passes in a hundredth of a second or so: that from the atomic bomb will generally last many times longer, exerting its force against the structure walls for a longer time, and usually causing more severe damage.

The shock moves at first much faster than sound, but in a rather short distance comes down nearly to the speed of sound in normal air, about a thousand feet per second, or seven hundred and fifty miles an hour. Thus the two or three miles of Hiroshima which saw destruction from blast were flattened in the time it took the shock to cross that distance, perhaps ten or fifteen seconds.

**THE HEAT OF THE BOMB.** We lay on the ground nine miles from the tower in the desert where the first bomb was ready to detonate. The night was cold; the thin air of the high desert just before dawn made us shiver even though it was mid-July. Then came the blinding blue-white flash of the bomb and simultaneously the heat of the noon-day sun full on the face. That great heat out of the cold dawn at ten miles distance is for all of us who were at

Base Camp the most deeply remembered experience. The bomb radiates a not negligible fraction of its total energy in infra-red, visible, and ultra-violet light. Its average temperature in the first second or so, when the ball of fire has opened up until there is a sizeable surface to radiate, is like that of the sun, or perhaps somewhat hotter. The effect at ten miles is that of many seconds of solar radiation delivered in a much shorter time. At one mile distance the radiation intensity is one hundred times greater than that we experienced. This terrible flash heat deeply burned most of the men and women in the street within about a mile from the explosion at Hiroshima. Many light cloth and wooden objects—curtains, mats—were set on fire. The flash was so short that no one could move during its main brilliance. As a result the shadow of the nose was sunburned into the skin of many present at the explosion in Hiroshima. We saw a horse with the shadow of a rail fence unburned on his flank, which was elsewhere raw and hairless. This radiant heat is after the blast the most important source of damage. Tens of thousands of dead and injured, and scores of secondary fires can be ascribed to the radiation of the bomb.

**NUCLEAR EFFECTS: GAMMA RAYS, NEUTRONS, AND THE FISSION FRAGMENTS.** For every uranium atom fissioned in the bomb, two fission fragments are produced. By the time the ball of fire has formed, these fragments are no longer screened by the dense matter of the bomb, but only by the dilute vapour of the bomb's debris. Thus the delayed neutrons they emit, and the gamma rays associated with the beta decay of the typical fission fragment, can freely irradiate the outside world.

About one neutron is produced by the fission fragments for every hundred fissions in the bomb. These neutrons spread out in all directions. They are however rather

rapidly slowed down and finally absorbed by the nitrogen nuclei of the air, and do not reach any sizeable distance in great number. At Hiroshima Professor Nishina and his staff collected samples of every kind from the region below the bomb. Artificial radioactivity had been induced by neutron capture in many elements. In samples of phosphorus which they prepared from the bones of the many dead whose bodies were recovered within a kilometre of the blast the fifteen-day activity of phosphorus was especially strong. From such measurements they were able to estimate the number of fissions which had taken place. But the amount of neutrons reaching the ground from the height at which the bomb detonated was too small to induce any activity of more than laboratory significance. At the desert test, sodium activity in the salt of the desert floor was strongly excited. It is likely that few persons were injured by the neutrons emerging at Hiroshima or Nagasaki.

This is not true for the gamma rays. They too are emitted from the fission fragments into the air. We normally think of gamma rays as being very penetrating. Compared to the neutrons, this is true. But compared to visible light, gamma rays cannot pass through very thick layers of air. The energy of gammas is so much larger than the binding energies of electrons in atoms that every atom looks much like any other atom to a gamma ray. Ordinary light on the other hand finds air transparent, metal totally opaque. But to gamma rays air or earth offer the same barrier, weight for weight. Now, a thousand yards in air corresponds in mass to about one yard in water, or two feet in earth. Two feet of earth represent a rather heavy shield for gamma rays, and a few thousand yards, if you remember the added effect of the inverse square law as the distance increases, is a formidable shield, better than that installed at Hanford. Let us make a small computation. Suppose that two or three gamma rays are emitted for every one hundred

fissions (as with delayed neutrons) in the seconds that it takes to produce the ball of fire. This represents more than  $10^{24}$  gamma rays. At one kilometre, neglecting the effect of the absorption of the air, about  $10^{12}$  gamma rays strike every square centimetre. The air shielding is small at this distance—perhaps as much as a factor of ten, but not more—and the actual irradiation would be about that which physicians estimate as a minimum lethal dose. Many persons at even larger distances in Hiroshima and Nagasaki died from gamma radiation. Three thousand yards further, however, the dose received would be down by a factor of nine from the inverse square effect of distance alone, and by about a thousand from the six feet of earth equivalent which the additional air represents. So at two miles distance there can be no noticeable effect of the gamma rays from the explosion.

Some of the fission fragments may be blown into the ground. At the test shot, Trinity, the bomb exploded only a hundred or so feet above the surface on a steel tower. The ball of fire containing the vaporized fission fragments rested on the desert sands. A portion of these active atoms became fixed in the glassy slag which was the imprint of the ball of fire. This material remained on the ground, and did not rise when the ball of fire drifted into the air. The region of the crater thus was made very radioactive. Early entry into this area was possible only in the lead-lined Sherman tanks which rumbled in the first two hours into the centre of the crater. The short-lived fission products gradually decayed. About a month after the explosion, the activity was down by a factor of hundreds from the activity observed when the tanks made their initial survey. A party of reporters toured the central region. But even then the ground was active, and no one would have liked to make camp at that blasted spot. The collecting of active samples of the green glass, which has become tacitly named

“trinitite”, is still possible. The piece on my desk will still drive the counting dial of a Geiger-Muller detector set at staccato speed.

At Hiroshima and Nagasaki, the bomb was detonated high in the air. This was done both to enhance the energy of the shock wave, by taking advantage of a reflected shock from the surface of the ground, and to lessen the radioactive contamination of the earth. The ball of fire did not touch the ground. Very little of the fission fragments reached the ground, and no dangerous activity was observed at any time. No casualties were caused in these cities by early entry into the region of the explosion.

As the cloud and the mushroom drift across the countryside, the fission fragments they hold will in part condense out on to dust or water droplets, and the activity will gradually shower down on to the surface of the earth far below. The details of this phenomenon are strongly dependent on the weather: a hard rain through the active cloud in the first few hours would deluge the surface with dangerously active water. As time passes, the activity decreases and the cloud spreads; the danger from the contamination lessens. The direct gamma radiation is well shielded by the few miles of air between the surface and the cloud high above the inversion layers. Only if the atoms of the fragments are brought closer to the earth, as by actually falling upon it, is there any sizeable irradiation of the surface. About twenty or thirty miles from Trinity there is a mesa a couple of miles wide and ten miles long on to which a rather considerable activity fell. The New Mexico range cattle which were grazing there developed very noticeable loss of hair, greyness, and even ulcerated sores on their backs. It is dry in that country; the cattle received the dust from the cloud, and it remained for weeks on their backs, close to the skin, representing a serious though not fatal local dosage of radiation. The beta rays from the active

material in contact with the hide of the animals much increased the effect.

A thousand miles away from Trinity, in Illinois, the cornfields lay in the hot sun and strong rains of the Midwestern summer. The corn straw from certain of these fields is used for manufacturing the paper in which some sensitive photographic film is wrapped for sale. The batches of paper prepared from corn harvested a week or two after the test shot proved unacceptable to the film manufacturers; it contained enough radioactive contamination to fog some of the film. A physicist testing some Geiger counters in Maryland, two thousand miles from the test shot, noted an inexplicable increase in the background activity of his instruments on July 19, which went away a few days later. Only when the news of the bomb over Japan was released did he see a reason, which he transmitted to the *Physical Review*. Local rains may have brought down some material from the dilute cloud passing over Maryland in the stratosphere winds. While there is no definite proof that either of these remote events were direct consequences of the first bomb explosion, their timing is most suggestive. It must be said that even more remote effects are not absurd. There are some  $10^{24}$  active atoms of fission fragments produced in the explosion. Weeks afterwards, there are still  $10^{18}$  atoms decaying per second. If these atoms had been uniformly mixed by the winds over a belt a hundred miles long, thousands of miles wide, and the full height of the atmosphere—which certainly overestimates the dilution—the resulting activity would still be conspicuous on an ordinary Geiger counter.

**THE DEATH OF A CITY.** In all that has gone before we have described the physics of the atomic bomb. But the bomb did not seem like an experiment in physics when we walked through the long half-ruined shed of the rail station

at Hiroshima and saw the litters of the blackened wounded and dying. The bomb is a weapon: the most deadly and terrible weapon yet devised. Against any city in the world from New York and London to the hundreds of large towns like Hiroshima and Nagasaki, the bomb is a threat. In any of man's cities a strike from a single atomic bomb will claim some hundred thousand deaths and some square miles of blackened ruin. The shock wave will wreck brick as it does wood, the gamma rays will kill men with white skin as it does those who have a yellow pigment, the fire will burn the cotton clothing of Manchester manufacture as well as it did that of Kyoto. And the bombs, if they come again, will not come in ones or twos, but in hundreds or thousands. Their coming will wreck not cities, but whole nations.

Physicists have learned to say more than physics these days. I hope the reader will see the propriety of ending this partial account of the work of the great laboratory at Los Alamos with a few sentences from a speech of its wartime director, Robert Oppenheimer:

"... If atomic bombs are to be added as new weapons to the arsenals of a warring world, or to the arsenals of nations preparing for war, then the time will come when mankind will curse the names of Los Alamos and of Hiroshima.

"The peoples of this world must unite, or they will perish. This war, that has ravaged so much of the earth, has written these words. The atomic bomb has spelled them out for all men to understand. Other men have spoken them, in other times, of other wars, of other weapons. They have not prevailed. There are some, misled by a false sense of human history, who hold that they will not prevail to-day. It is not for us to believe that. By our works we are committed, committed to a world united, before this common peril, in law, and in humanity."

# RADIOACTIVE TRACERS

By M. Argo and E. Teller

**INTRODUCTION.** The spectacular results of the atomic bomb demonstrated the wartime applications of atomic energy. As long as war is even a remote possibility questions of the atomic bomb have paramount importance. The peacetime application of the tremendous energy liberated from a small amount of material seems at first sight hardly less impressive. But while utilization of such power is possible, it meets with many difficulties. Complete replacement of the usual energy sources by atomic energy must certainly not be expected. One of the main difficulties lies in the radiation which always accompanies energy liberated by fission, a radiation which is so intense where considerable power is generated that human beings can be in the vicinity only behind the protection of thick and heavy shields (see page 84).

One use which will become very important is of a more subtle type. It is based on the fact that the radiation just mentioned, which is so harmful when present in big amounts, can be detected in very small amounts which are entirely harmless to the human body. This radiation is interesting because much of it originates in atoms which in practically all other properties are completely similar to ordinary atoms (which do not radiate). These new kinds of atoms can therefore be employed in biological, chemical, and industrial processes as "tagged" atoms which can easily be recognized, and this makes them exceedingly useful. As an example let us consider the atom known as carbon 14, which is a radioactive counterpart of normal carbon or carbon 12. In any chemical compound this

radioactive substance behaves like any other atom of carbon. Its radiation, however, will be detectable if a thousandth of a milligram of carbon 14 is present and will be dangerous only if this amount is multiplied by several thousand. Thus a considerable range is left for safe application.

It can easily be realized that much valuable and, indeed, unique information can be obtained by following the path of a batch of atoms, labelled by their radioactivity. We shall give several examples how such atoms have been used in the past or may be used in the future to understand the mechanism of certain physical processes and chemical reactions. In particular, the functioning of living organisms may be studied, with this fine tool, in much greater detail than was possible so far.

But before entering the field of these applications we must learn more about the nature of radioactive atoms.

**WHAT IS CARBON 14?** The structure of atoms and nuclei has already been discussed on pages 19-36. It will be remembered that all atomic nuclei are made up of an aggregate of protons and neutrons. The most common type of carbon nucleus has six protons and six neutrons or a total of twelve heavy particles, hence we call it carbon 12. Other carbon nuclei have five, seven, or eight neutrons giving carbon 11, carbon 13, and carbon 14 respectively.

Carbon 14, whose nucleus is two neutrons removed from the balance is radioactive and tends to eject an electron from the nucleus (or rather from a neutron within the nucleus). This transforms a neutron (which has no charge) into a (positive) proton. Because of the additional proton, one more electron attaches itself, and the resulting atom no longer resembles carbon but nitrogen, having seven protons and seven neutrons in its nucleus and seven electrons round it. The electron emitted in the process can be observed by various means as discussed on pages 130 *et seq.*

This process of conversion does not take place simultaneously in all atoms of radioactive carbon nor does it occur immediately upon the formation of carbon 14. Many of its atoms continue to exist for thousands of years. If one has a quantity of such carbon, however, one will find that on the average, half of the quantity has converted itself, or "decayed", into nitrogen at the end of three thousand years, and after another three thousand years, only one quarter will be left. The time in which one half of the material decays is known as the half-life of the isotope. Some radioactive elements have longer half-lives, others have shorter ones. Some are too short even to provide time to recognize the isotopes' existence; others are of the order of seconds, minutes, days, and so forth. If an element has a short half-life this means the rate of disintegration is great, and the large number of particles emitted per second makes the element easy to detect.

**PRODUCTION OF RADIOACTIVE ISOTOPES.** One way to produce the labelled carbon 14 is to bombard carbon with neutrons. Most of the ordinary carbon atoms are carbon 12. But one per cent of the atoms are carbon 13. If these capture a neutron they get transformed into carbon 14. This is only one example of the production of radioactive isotopes of the elements by neutron capture. There are many others. The development of the chain reacting pile has greatly facilitated this method of production because of the great number of neutrons escaping from the pile.

It will be remembered that uranium nucleus can split into parts of varying relative sizes; therefore a great variety of active nuclei are formed. Isotopes of about 22 elements are among these fission products, including, for instance, bromine, iodine, molybdenum, and silver. Both the fission products and neutrons are extremely abundant by-products

of the pile, and radioactive substances are therefore now available in quantities vastly greater than were ever applied before in research or in medicine.

In the foregoing discussion we mentioned only the kind of radioactive isotopes which eject an electron from a nucleus. There are other isotopes in which positrons (positive electrons) are emitted, for instance carbon 11. Furthermore there are some isotopes which emit alpha particles (helium nuclei), as for instance radium. Radioactive isotopes of this kind are not likely to be produced in such great abundance as electron-emitting substances. We shall therefore limit the discussion to the latter.

**DETECTION.** It has been mentioned that radioactive atoms can be detected by the radiations they emit. The characteristic property of the substances which we are going to discuss is the emission of electrons. The ejection of a electron may, however, be accompanied by further radiation. It happens frequently that, after the electron has escaped, the nucleus remains in an excited state, containing an excess of energy, of which the nucleus then rids itself by emitting electro-magnetic waves. These waves are akin to visible light, but they have a much higher frequency. Actually they are more nearly like X-rays, electro-magnetic waves with frequencies some thousand times greater than the frequencies found in visible light. But the electro-magnetic waves emitted by nuclei surpass even the X-rays in frequency and also in power of penetration.

The electrons emitted by radioactive substances are called beta rays. The accompanying electro-magnetic radiation is called gamma radiation. Gamma rays are extremely penetrating. The extent to which they are absorbed in materials depends on the energy they carry; the penetrating power increases with increasing energy. The same is true

about beta rays, but, on the whole, beta rays are much more easily absorbed than gamma rays. About two inches of aluminium are needed to absorb half of the energy of an average gamma ray. Complete absorption can be obtained for an average beta ray by thirty times less aluminium. Low-energy beta rays are absorbed in exceedingly thin layers of matter and this makes the detection of some radioactive materials difficult because special care is needed to get the radiation into the detecting device.

A number of instruments for recording not only the presence but the number of beta and gamma rays are in use. The most common of these is the Geiger-Müller counter (briefly G-M counter). The sensitive part of most counters is a volume filled with gas. If a beta ray, i.e., a fast electron, enters this volume, it immediately begins to share its energy with the atoms or molecules of the gas by colliding with the gas molecules. Usually the amount of energy given to the gas molecule is sufficient to rip off one of the outer electrons of the gas atoms, leaving the atom with an excess positive charge. The process of separating the gas molecule into oppositely charged particles is called ionization; the positive and negative particles are called ions. The more energy the beta ray has, the more ions it can

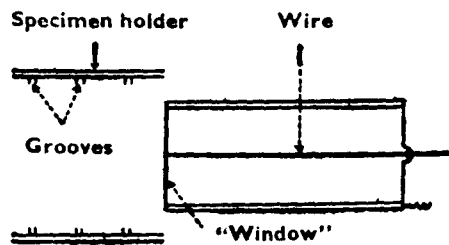


FIG. 2. GEIGER-MÜLLER COUNTER TUBE.

The specimen slides into the grooves at different distances from the window (see also Fig. 6, page 138)

produce. Gamma rays ionize the gas indirectly, first colliding with an electron, imparting to it a considerable amount of energy and leaving the electron to behave as a beta ray does.

The Geiger-Müller counter tube consists of a cylinder made of conducting material. Stretched along the axis of the cylinder is a fine wire (see Fig. 2). The tube is first evacuated and then filled with gas at a pressure usually about a fifth of atmospheric pressure. A good gas mixture has been found to be 90% argon and 10% ethyl alcohol. An electric potential of about a thousand volts is applied between the cylinder and the wire, making the wire positive. This potential is low enough to secure that in the absence of ions no current flows. Now assume a beta ray enters. It starts to ionize the gas and the positive ions move toward the cylinder wall, the electrons to the positive wire. These electrons are accelerated by the electric potential and ionize further gas particles. In this way an avalanche of electrons is produced. The potential is adjusted so that a single electron will start an avalanche powerful enough to be recorded, yet one which stops when all the electrons have reached the wire. After that, in a somewhat slower process, the heavier positive ions are drawn to the outer wall and then the tube is ready to count another beta ray which might enter. The whole process takes approximately one ten-thousandth of a second.

The current developed may be fed through an electronic device to amplify it (just as a radio signal is amplified) and then to a mechanical or electronic recording device. The energy obtained from a G-M tube is not the energy of the particle which enters but is drawn from the energy stored in the voltage supply of the counter. The particle merely serves to trigger the sudden release of this energy.

Owing to the different nature of beta and gamma rays their detection presents somewhat different problems.

Gamma rays will easily penetrate the walls of the counter but once inside they will lose energy to the gas at a correspondingly low rate. Therefore only one out of a hundred gamma quanta passing through the counter will be recorded. On the other hand beta rays produce ions inside the counter more copiously and nearly every one of them is counted; but it is more difficult to let them enter. Beta counters are made with thin walls or provided with a thin window (usually of aluminium foil or mica) with a thickness of the order of a thousandth of an inch. In some cases where no gammas are emitted and the betas have low energy, no window can be conveniently constructed which will allow the radiation to enter the counter. In such cases it is usual, for instance in the case of carbon 14, to introduce a compound containing the radioactive element into the counter itself.

Radioactive atoms are not the only ones which can be or have been used as marked atoms or tracers in research. Other rare isotopes like heavy hydrogen (hydrogen 2, consisting of a neutron and a proton) or carbon 13 (consisting of six protons and seven neutrons) have been used, particularly in biological work. In the case of oxygen and nitrogen the stable isotopes oxygen 18 and nitrogen 15 are used since all the radioactive isotopes of oxygen and nitrogen have very short half-lives. In all these cases the detection of the marked atoms is a more elaborate process demanding the use of a mass spectrograph (see the article on isotope separation). If one wants to detect radioactive isotopes the only apparatus needed is a counter and an amplifier system. This apparatus is in principle not more complicated than a common radio set and there is little doubt that in due time it will become both cheap and available.

**APPLICATIONS.** Radioactive tracers have already been used in many important experiments, but before the war these

experiments were limited by the scarcity of artificially produced radioactive isotopes. These isotopes were obtained in small amounts by bombarding various materials with high energy ion beams produced in quite costly apparatus such as the cyclotron. When the development of chain reacting piles made radioactive materials available in much greater quantity, wartime secrecy stood in the way of distributing these valuable products to research institutions. Now that the secrecy has at least partly been lifted we may expect that in the near future investigations in the most varied fields will obtain considerable impetus from this powerful and simple tool.

In the following pages we shall mention a few experiments that have been actually carried out with the help of these substances. We shall also try to give an impression of the probable future scope of applications by discussing possible new lines of research. Some of these may seem fantastic, some may not be fruitful and some may be actually impossible, but we hope to be able by our discussion to show the breadth and importance of the field.

One rather fantastic application, but one not altogether impossible, is the tagging of air masses. Modern meteorology is based on following the course of air masses and the changes they undergo as they move. This has made long-range weather forecasting possible. In order to identify air masses one had to rely on properties such as humidity, which can vary and thus occasionally lead to some ambiguity. Also one cannot follow an air mass unless it happens to differ from neighbouring masses in some more or less permanent characteristic. The use of tracers will allow us to observe more exactly the travel and mixing of air masses. One has to introduce the tracer as very fine dust or, preferably, as a gas. Geiger-Müller counters placed in the usual ascending balloons would then locate the air mass and by measuring the amount of radioactivity would give

some idea of how much the air mass had become mixed with non-radioactive air from adjacent masses. The one apparent objection to this application is the large amount of material necessary to tag the atmosphere. Actually air masses were tagged unintentionally when the atomic bombs were set off. The resulting radioactivity was found in high altitude air masses one month later, after it had travelled once around the earth. Much smaller amounts of active material might be sufficient to tag small air masses for short periods.

Coming down to earth, one may use radioactivity to observe the motion or the surface wear of internal parts of machines. Iron has a gamma-emitting isotope with a half-life of 43 days. This can be used to impregnate the steel from which the parts are made. It would appear simpler to paint the surface a distinctive colour or use a layer of different material on the surface; but then one would have to disassemble the machine in order to observe the surfaces. The gamma activity, however, could be measured through the walls of the machine. In this way one could notice if an inner surface is worn off or if a part of the machine does not move as it should. In Babbitt metal, from which bearings are made, the gamma-emitting isotope of antimony with a 60-day half-life could be used. The rate at which the bearings wear could then be determined by measuring the radioactivity appearing in the lubricant.

Radioactive isotopes may be used to make easier the task of the analytical chemist. Quantitative analysis is the procedure for finding the total amount of a certain element in a given sample. To achieve this one must separate the element in question (or a well-known compound of it) from the sample, and the main difficulty lies in making sure that nothing is lost. In the proposed method a radioactive isotope of the element is added in a minute amount, giving the sample a certain activity per gram weight. The usual separation is then performed and the activity of the pure

resulting preparation is measured. The increase in the activity per gram is inversely proportional to the original concentration of the element for which one has analyzed. The losses occurring during the separation are of no importance. The only important thing is to obtain in the end a pure sample.

The really important applications are in the fields of medicine and biology where one has familiar objects whose interior details and functions are not well known. Unfortunately there are no usable radioactive tracers for the essential elements, nitrogen and oxygen. For two others, carbon and hydrogen, the tracers, C14 and H3, are not cheap and the inactive isotopes, C13 and H2, may continue to be used. It cannot be said which will be more available; it can be said that the radioactive isotopes will be more easily detectable. Radioactive carbon has already been used in studying the path and the history of lactic acid, a waste product produced in the muscles by exertion.\* It was found that the lactates can be resynthesized in the liver into sugars and other carbohydrates.

The radioactive isotopes of the other elements like sulphur, iron, phosphorus, or iodine are easy to produce and detect and are also of vital importance to organisms. Radioactive iron has been used to determine the volume of blood in dogs by a technique which can be applied to other animals and to man. One dog is fed radioactive iron which is deposited in the hemoglobin of the red blood cells. A known number of active cells are then extracted and injected into a second dog. The dilution of these active cells is then a direct measure of the blood volume.†

Apart from these examples of investigation gaining

\*Hastings, Kistiakowsky, Cramer, Klemperer, Solomon and Venneland: *Science* 91, 421 (1940).

†Whipple, Hahn, Balfour, Ross, Bale: Red Cell Volume, Circulating and Total, as Determined by Radio-iron. *Science* 91, 87 (1941).

some understanding of the fundamental properties and reactions of organisms, radioactive elements can provide a useful tool in diagnosing the abnormalities of organisms. It is often a difficult task to decide at what point a gangrenous limb should be amputated. We have in mind the case where gangrene is due to poor circulation of the blood. If one introduces radioactive sodium into the blood stream, the blood will carry the radioactivity as far as the circulation extends. The radioactive sodium has a gamma ray which can be detected merely by moving a counter over the surface of the limb. The point at which the gamma radiation is no longer found locates the point above which one must amputate.

Cancer is another case where diseased tissues must often be removed by surgery. One reason a cancer operation may be unsuccessful is that small pieces of the diseased tissue might have broken off and might have been carried by the blood stream to other parts of the body, where they may not be detected until irritation of other organs has begun. It would be of great help in cancer therapy if these loose particles of cancerous tissue could be traced. In general we do not see at present any way of doing this. In the special case of cancer of the thyroid, however, there seems to be some hope. Radioactive iodine, like normal iodine, is taken up by this gland. Even broken-off pieces of the cancerous thyroid tissue in other parts of the body will take up iodine. In this way these dangerous centres of abnormal thyroid tissue may be found by moving a counter over the surface of the body.

The tracer method may also make it possible to check long-range biological effects. It is likely that the formation of caries is connected with the rate of deposition of phosphorus in the teeth. But it is not possible to check this assumption except by somewhat indirect and statistical methods. Furthermore, it is not easy to find out what

factors control the deposition of phosphorus. These questions can now be settled by including radio-phosphorus in the diet and investigating how much of the radioactivity appears in the teeth.

Other slow processes may also be investigated. Radio-calcium may prove valuable in investigating arteriosclerosis which is associated with the deposition of calcium in the arteries. This might make possible early detection and it also might yield a fast method for testing preventive measures or cures. In fact the detection of disorders and the testing of curative procedures are second in importance only to an easy and reliable cure.

Generally speaking, it seems not unlikely that the following of metabolism by radioactive tracers will become a routine procedure in hospitals and even in private medical examinations. Of course, the usefulness of such tests would have to be established by experiments on metabolism in healthy and diseased organisms.

Diagnosis, while perhaps the most important, is not the only use of radioactive materials in medicine. Hitherto radiation therapy could be carried out only with the help of costly apparatus and materials. The large-scale production of radioactive substances will make this type of treatment generally cheaper and more available. Both in the most important field of destruction of cancerous tissue and for such minor applications as the removal of warts and ringworm infections there will be a widespread demand for radioactive substances. In some cases these short-lived isotopes could be applied inexpensively in the form of plasters and packings; the very fact of their short radioactive lifetime will minimize dangers of overexposure. Internal cancer and widespread cancer can very often not be treated by radiotherapy because healthy tissues are apt to be damaged by the radiation. It is a great, though perhaps distant hope, that with the help of radioactive substances

specific and localized treatments can be achieved. For instance the capacity of the thyroid gland for accumulating iodine, which we have mentioned before, may be used to concentrate the radiation of an active isotope of iodine onto the cancerous tissue in the gland without endangering healthy tissues nearby. With the range of radioactive substances now available, many of which are isotopes of normal constituents of body tissues, one might look for other instances in which the radioactive materials attach themselves to the cancerous growth or the infected organ. Experiments with both phosphorus and strontium in the treatment of leukæmia show that the leukæmic tissue absorbs more phosphorus than normal bone and that the radioactive material can thus be placed for most effective irradiation.\* However, the greatest progress in the fight against cancer and many other diseases may come from fundamental research in biology, undertaken merely for the better understanding of physiological processes rather than for a specific aim.

Agriculture is also expected to make its demand on the supply of radioactive materials. New variants and even new species are occasionally formed by so-called mutations, and it is well known that the frequency of mutations can be increased by radioactive irradiation. Experimentation with plant variations might be opened to the trained horticulturalist. In fact it is likely that the production of new plant species will soon be limited mostly by the supply of trained plant breeders who can recognize new and valuable variants rather than by the possibility of producing variants.

Perhaps the study of fertilizer efficiency under the actual growing conditions will become the most widespread of all applications. The use that the plant makes of elements supplied in fertilizer can be determined easily and quickly

\*Lawrence, J. H., Scott, K. G. and Tuttle, L. W. *Int. Clin. N.S.* 3 (1939).

by measuring the amount of radioactivity appearing in the plant owing to the uptake of tagged atoms added to the fertilizer. The variations of soil conditions from farm to farm need no longer be a factor of uncertainty in fertilizing, for each farmer can run a series of tests to find the fertilizer best adapted to his own land.

The suggested widespread applications bring us to the question of the safety of wholesale distribution. Like motor cars or gunpowder, radioactive materials can be dangerous through ignorance, accident or intentional misuse. For medical purposes, after proper instruction, doctors will handle active isotopes as trustfully and as trustworthily as any drug. Certainly they are not more dangerous than many drugs in common use. For industry, agriculture, and other fields, distribution should be made somewhat on the same careful basis as that of recognized poisons. It must be remembered that for many uses only very small, unharmed amounts are necessary. While strict rules are certainly needed, unnecessarily strict rules must not be allowed to strangle the progress.

We have seen that radioactive products can be used not merely to increase our wealth and our power to wage war, but also to widen our knowledge and probably to save human lives. These wonderful tools should be made available at an early date to all scientists of the world. This would be one way in which the progress of nuclear science instead of creating alarm and suspicion might be made to promote world-wide co-operation.

## THE TOOLS OF NUCLEAR PHYSICS

*By O. R. Frisch*

THE recent spectacular success in unlocking the large amounts of energy contained in heavy atomic nuclei was made possible through a long and patient process of investigation and interpretation through which physicists gradually gained some insight into the structure of that small core of very dense matter which is at the centre of every chemical atom and comprises nearly all its weight. Becquerel's chance discovery of what came to be called radioactive phenomena started a series of dramatic investigations through which some of our firmest scientific beliefs, such as the immutability of elements and the conservation of both mass and energy, came to be replaced by wider concepts, and which laid the foundation for our present knowledge of the structure of atoms. It was soon discovered that radioactive bodies liberated, at a very low rate, very large amounts of energy; but for a long time all attempts to control the release of these energies were utterly unsuccessful. The amounts of energy which were released by "atom splitters", although tremendous in proportion to the minute amounts of matter involved, were ridiculously small compared with human needs. Yet the effort of the atom splitters was not wasted, for through their labours the knowledge was accumulated which eventually permitted us to solve the problem of controlled release of nuclear energies.

Nuclear physics is usually understood to mean that field of knowledge and endeavour which concerns the trans-

formations of atomic nuclei. The electric charge, the mass, the magnetic moment, the size and the shape of atomic nuclei have been explored by means which do not involve their transformation; these investigations are not usually regarded as part of nuclear physics.

Until around 1930 nuclear physics was essentially the study of radioactivity. The task of the physicist was to observe what happened; he did not have to produce the phenomena he wanted to study. He had to isolate, out of a number of things happening all at once, the one to which he wanted to pay special attention, and he had to set up instruments which were sufficiently sensitive to the phenomenon in question.

In later years we have learnt to produce nuclear transformations artificially, and now the observation of radioactive substances forms only a small part of the activities of nuclear physicists. Large and spectacular machines (of which the cyclotron is only one much publicised example) were built for the "smashing of atoms", and large and spectacular advances in our knowledge have accrued from their use. At the same time, the tools for observing nuclear transformation are still basically the same as before 1930, although their scope, speed and accuracy is constantly being increased.

I shall therefore begin my report on the tools of nuclear physics with a description of the "detecting tools" used to observe the phenomena which accompany nuclear transformations (spontaneous or artificial). This will be followed by a chapter on the "attacking tools" used to produce nuclear transformations; their description will be necessarily incomplete, owing to the great complexity of these machines. Finally I shall discuss the ways in which these two kinds of tools are employed together, and some of the techniques which are needed in order to isolate one particular phenomenon for study.

*Detecting Tools*

ALL nuclear transformations result (directly or indirectly) in the appearance of fast-moving, electrically charged particles. On their way through air (or some other gas) these particles collide with molecules on their path, frequently tearing off an electron in the process; this electron usually attaches itself to some nearby molecule. As a result, the particle leaves a trail consisting of molecules some of which have lost an electron and are thus positively charged while others have gained an additional electron and therefore carry a negative charge. Such electrically charged molecules (or atoms) are called ions, and the process by which they originate ionization.

The ionization of gases by fast-moving electrically charged particles forms the basis of nearly all existing methods for the observation of nuclear transformations.

**THE CLOUD CHAMBER.** C. T. R. Wilson (Cambridge) invented a method of making the trail of ions visible. The method consists in attaching a droplet of water to each ion, by condensing moisture out of the surrounding air. When air is compressed it becomes hotter (as your bicycle pump will tell you), when it is expanded it becomes colder. Water, if left in contact with a limited volume of air, will evaporate only until the air is saturated with water vapour; the amount of moisture needed to saturate the air is greater at higher temperature. If moist, saturated air is suddenly expanded it comes to contain more moisture than its lowered temperature warrants; it is supersaturated. The excess moisture condenses on whatever is at hand and if the supersaturation is strong enough individual ions can act as nuclei for condensation. Each ion then becomes a small droplet of water, and the trail of ions looks like a fine streak of cloud not unlike the white trails which are sometimes produced by high-flying aircraft. To summarize,

the method consists in letting the particles under investigation pass through moist air which is then suddenly expanded.

The instrument designed to put this method into effect is called a cloud chamber or expansion chamber. Numerous types have been built to suit special requirements. A fairly typical chamber is shown diagrammatically in Fig. 3.

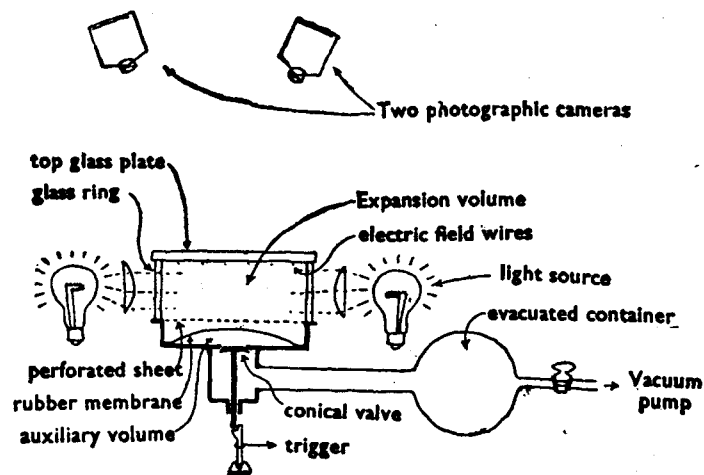


FIG. 3. CLOUD CHAMBER, SCHEMATICAL

The top is a glass plate, the sides are formed by a glass ring. The bottom of the observation volume is a perforated metal sheet covered with black velvet, which acts as a background against which the cloud tracks can stand out clearly. Below this there is a rubber membrane which separates the expansion volume from the auxiliary volume. The latter is at first filled with air at a suitable pressure (adjusted with the help of a manometer), pushing the rubber membrane up, as indicated in the diagram. When the

expansion is wanted the conical valve is opened; air rushes from the auxiliary volume into a large, previously evacuated, container, sucking the rubber membrane against the bottom plate. In this way the air in the observation volume is suddenly expanded by a definite amount. The perforated sheet and the velvet prevent any eddies, created by the sudden motion of the rubber membrane, from disturbing the droplets in the observation volume. Before assembling the chamber, the velvet is made wet to provide a source of moisture.

Unless fixed by the formation of droplets, the ions take part in the thermal agitation of the gas molecules and drift apart rapidly; within a tenth of a second the trail has become so diffuse that it would give only a blurred wisp of fog if an expansion were made. In order to clear the cloud chamber of these old ions one has to have an electric field. Several fine wires near the top plate, kept at 100 volts above the potential of the perforated metal plate, will sweep out all ions as fast as they are produced, within a fraction of a second; the electric field can be switched off automatically, at the instant of the expansion.

The track of droplets remains visible and undistorted only for a second or less since the droplets quickly fall to the bottom. It is usual to take a photograph of the tracks within a fraction of a second after the expansion. Ordinary filament bulbs are frequently used as a light source; they give a very intense flash of light if momentarily run at about twice their rated voltage, and will yet survive a large number of flashes. Frequently two pictures are taken simultaneously from two different directions, so as to get a stereoscopic effect; from the two pictures it is possible to reconstruct the location of the tracks in the chamber completely, in all three dimensions.

Some typical cloud chamber pictures are shown on plates 10 and 11. In plate 11 alpha particles were obtained by putting

a strong polonium sample right inside the chamber; as a result a large number of alpha tracks were formed during a single expansion. It is seen that all the tracks have very nearly the same length. Alpha particles have a well defined range which depends on their velocity. As the particle travels through the air it loses speed until it is no longer able to ionize air molecules, and its track comes to an end. Measurement of the range is a convenient way to determine the speed, and hence the energy, of the particle.

Electrons (see plate 10) give tracks which are far less dense and straight, because they produce far fewer ions over the same path length, and because they are more easily deflected by collisions. Their range is ill defined and usually much greater than that of alpha particles. The best method for measuring their energy is to place copper coils round the chamber and send an electric current through the coils, creating a magnetic field in the chamber. In such a field, electrons are deflected so that they run in a curved rather than in a straight line. There is a simple relation between the amount of curvature, the magnetic field intensity, and the energy of the electron, from which the energy can be calculated.

The cloud chamber can also detect gamma rays and neutrons although they carry no electric charge and hence form no track themselves. Gamma rays are light quanta (photons) of high energy; they can impart enough energy to an electron for it to make a track in a cloud chamber. Neutrons do not interact measurably with electrons, but they do with nuclei. In colliding, for instance, with a hydrogen nucleus (a proton) the neutron rebounds, giving part of its energy to the proton. Hence a cloud chamber containing hydrogen will detect fast neutrons, through the tracks of protons which start inside the chamber for no "visible" reason. Protons give straight tracks with a well defined range like alpha particles, only somewhat thinner.

The visual and detailed character and the wonderful directness of the information which a cloud chamber supplies are advantages too obvious to need elaboration. Much of our confidence in the truth of our detailed descriptions of nuclear processes derives from the documentary evidence obtained from cloud chamber pictures. The drawbacks are better explained later, by comparison with other research tools.

**THE ELECTROSCOPE.** The electroscope is the oldest research tool of the nuclear physicist, indeed the oldest electrical measuring instrument. It gives only the most primitive sort of information and is not very sensitive, but it is simple, reliable, and accurate. In a typical design, the main part is a strip of very thin gold foil, hanging along one side of a vertical metal rod which is mounted on a good electric insulator (usually a piece of sulphur) inside a metal can (see fig. 4). An electric charge is given to the rod by

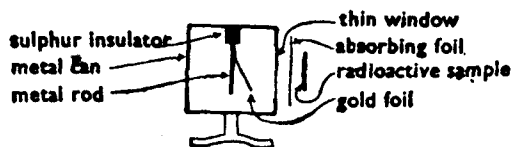


FIG. 4. ELECTROSCOPE, SCHEMATICAL

touching it momentarily with a charged wire (not shown in the diagram); the gold foil will then rise because of the mutual repulsion of the equal charges on it and on the rod. If there is no source of ionization present the rod will remain charged for a long time (many hours). If however the air in the can becomes ionized it becomes slightly conducting. Assuming, for instance, that the rod is positively charged, the negative ions will move towards it while the positive ions go to the wall of the can. As a result

the rod gets gradually discharged and the gold foil slowly moves back to its natural vertical position. This movement can be observed by a low-power microscope mounted on the can, and the speed of the movement (measured with the help of a stop watch) is an indication of the intensity of ionization.

In contrast to the cloud chamber, the electroscope tells nothing about the nature of the particles which cause the ionization. On the other hand it is quantitative, it tells accurately at what rate ions are being produced. By varying the conditions it is even possible to analyse the radiation in a rough way. For instance, if the can has a window of very thin aluminium foil and an active sample is placed in front of that window, alpha, beta and gamma rays are able to enter the can. Interposing a sheet of paper will stop the alpha particles, and the corresponding decrease in ionization—as measured by the slower motion of the gold foil—indicates which fraction of the ionization was due to the alpha particles. A 1/16" sheet of brass will stop all the beta rays (the electrons) and the residual weak ionization will be due to the gamma rays only. If one increases the thickness of the interposed absorber in small and accurately known steps and plots the observed ionization as a function of the absorber thickness one gets what is called the absorption curve of the radiations emitted from the sample. From this curve the composition of the radiation can be obtained in fair detail, and many properties of radioactive bodies have been determined in this fashion.

One drawback of the electroscope is its limited sensitivity. About a hundred alpha particles—or an even larger number of electrons—have to pass through the can to produce a visible shift of the gold foil. Numerous attempts have been made to improve the sensitivity of the electroscope and among the rather complicated instruments (called electrometers) which were developed there are

some which are so sensitive that the ionization due to a single alpha particle is not merely detectable but indeed accurately measurable. However these instruments are so delicate and so awkward to use that very little research has been done with them.

**THE PROPORTIONAL AMPLIFIER.** Efficient detection of the ionization due to individual particles became possible only through the development of the radio valve. A considerable effort was needed at first to develop amplifiers which would magnify the tiny input signals (.001 volt or less) to an output signal sufficiently large to be recorded and yet accurately proportional to the amount of ionization.

Greinacher in Switzerland, Ortner and Stetter in Austria and Wynn-Williams in England were the pioneers of this development.

At the input end of the amplifier is the ionization chamber which the particles have to enter in order to be recorded. Some typical ionization chambers are shown in fig. 5. The principal parts are the collecting electrode—a

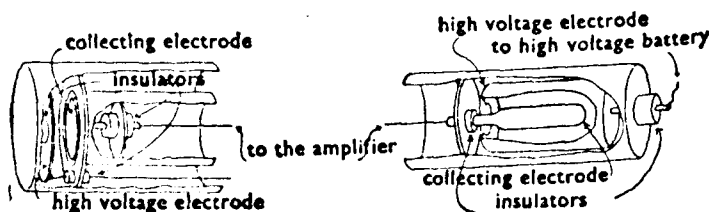


FIG. 5. IONIZATION CHAMBERS, SECTION VIEW

plate or rod of metal—which is connected to the input of the amplifier and the high-voltage electrode which is connected to a battery of a few hundred to a few thousand volts and which serves to create an electric field in the neighbourhood of the collecting electrode. The ions are set

in motion by this field, the positive ions being driven towards the negative electrode and vice versa.

Whenever an alpha particle runs through the chamber, leaving a trail of ions, a small current, representing the motion of the ions, begins to flow and continues (for a small fraction of a second) until all the ions have reached the electrodes. This brief current pulse charges the collecting electrode—and hence the input grid of the amplifier—to a potential slightly different from its normal value. This little potential jump is the signal which is magnified by the amplifier in the same way in which a radio amplifier magnifies the small signals picked up by the aerial.

There is a variety of recording devices which can be attached to the output end of the amplifier. The simplest and most common is a counting device such as is used in telephone exchanges to indicate the number of calls made by a customer during an accounting period. The device is set so that only pulses above a certain size will affect it; repeated counts with different settings give information on the distribution of pulse sizes, from which conclusions can be drawn as to the number and character of the particles passing through the chamber.

If one connects a loudspeaker to the output of the amplifier the individual particles become audible as sharp cracks above a persistent hissing noise. This noise is largely due to the random motion of the electrons in the first valve of the amplifier; by careful design it can be reduced but not entirely eliminated. It represents the limit to the size of signal that can still be detected; if a signal is so small that it disappears in the noise no amount of amplification will make it detectable. A particle has to create several hundred ions in order to produce a detectable signal; this is more than a fast electron will produce on passing through an ionization chamber of reasonable size. If one wants to detect individual electrons one must strengthen the

signal before it enters the amplifier. This can in fact be done.

**GAS MULTIPLICATION.** If the electric field in an ionization chamber is made strong enough the ions will move so fast that they themselves become capable of ionizing the gas. The newly created ions join the race and in turn produce further ions. Thus we get a growing avalanche of ions (somewhat similar to the avalanche of neutrons in an atomic bomb), and the number of ions originally produced becomes multiplied through their interaction with the gas.

To make use of this effect it is common to use a thin wire for the collecting electrode; close to the wire the electric field is very intense and with a modest voltage of about thousand volts on the other (cylindrical) electrode one can make it so strong that gas multiplication sets in. An ionization chamber designed in this fashion is frequently called a counter (see fig. 6). By carefully adjusting the

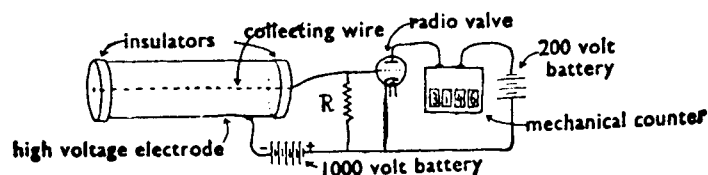


FIG. 6. G-M COUNTER AND RECORDING CIRCUIT

voltage one can obtain multiplication by factors up to a thousand and still get pulses which are approximately proportional to the original amount of ionization; used in this way the instrument is called a proportional counter. With increasing voltage the multiplication goes up very rapidly and eventually gets out of control; a single ion will then set off a discharge involving many millions of ions.

**THE GEIGER-MÜLLER COUNTER (OR G-M COUNTER).** Geiger and Müller (Germany) were the first to show how one could quench the discharge so that a fraction of a second later the counter is back in its original condition and ready for the next particle. Each discharge is vigorous enough to be detected by an electroscope, and some of the first investigations with this counter were indeed done by visual observation; however, this method is very tedious and later a simple amplifier was used to operate a mechanical counting device.

The quenching of the discharge can be achieved by making the resistance  $R$  (see fig. 6) very large, a thousand megohms or more, by filling the counter with a special gas mixture (for instance argon containing some alcohol vapour) or by having the amplifier reduce the voltage on the counter for a short time after each pulse. The first method is now little used because the counter takes too long to recover after each pulse; the other two methods both have their champions.

Since an ionizing particle produces all its ions practically at the same time (within a hundred-millionth of a second or less) each particle passing through a G-M counter will produce just one pulse, whether it ionizes only one gas molecule or many thousand, whether the particle is an electron or an alpha particle. However the main value of the G-M counter lies in its ability to count individual electrons. A large number of radioactive isotopes decay under emission of (positive or negative) electrons, and G-M counters are widely used to study this decay or to measure the amount of a certain isotope contained in a given sample. The use of radioactive tracers in chemistry, biology and medicine (see the article on Radioactive Tracers) has brought the G-M counter to numerous laboratories where no nuclear physicist has ever set foot.

Common to all counting methods are three limitations

which can be labelled briefly by the words: statistics, background, and resolution.

Nuclear events happen at random, independently of one another. Therefore, the number of events in a given time interval is subject to fluctuations such as are encountered in all statistical phenomena. If 100 pulses are observed in one particular minute this does not mean that the average pulse rate is exactly 100 per minute; it merely indicates that the average is likely to lie between 90 and 110 per minute, although a value even further from 100 is by no means excluded. In general, if  $N$  pulses are observed the true average is likely to lie between  $N + \sqrt{N}$  and  $N - \sqrt{N}$ . The uncertainty— $\sqrt{N}$ —grows more slowly than  $N$  itself and hence the accuracy improves as more pulses are counted. If the rate at which pulses occur is low one has to run the experiment a long time to accumulate a sufficient number of pulses. At very low rates the time required becomes excessive owing to the presence of the "background".

All common materials (glass, metals etc.) contain traces of radioactive substances, and every counter (or ionization chamber) will therefore occasionally produce pulses all by itself. For each counter this background has to be determined and subtracted from the result of every experiment. This correction becomes relatively large and uncertain if the effect to be measured is very weak.

For instance, if a G-M counter has a background of 30 pulses per minute, the measurement of a sample which produces only one additional pulse per minute is almost impossible. If one works for two hours—one to measure the background, one to measure the sample—one should ideally get  $30 \times 60 = 1800$  in the first run and  $(30 + 1) \times 60 = 1860$  counts in the second. Each of these runs is however affected by a statistical uncertainty of about  $\sqrt{1800} = 43$ ; the expected difference of 60 therefore lies at the verge of

the statistical uncertainty and its very existence is still doubtful after those two hours' counting. It would take about fifty hours to obtain the strength of the sample with an uncertainty of plus or minus twenty per cent, which is still very inaccurate.

If the problem allows it one will try to arrange for a high counting rate so that the required accuracy can be reached in a short time. This means, however, that the pulses get very close together and occasionally two happen in such quick succession that they are not resolved, and only one is recorded. Mechanical counting devices usually need one hundredth of a second or more to record a pulse, and if another pulse occurs within this time it is not recorded. Hence with increasing counting rate an increasing proportion of pulses is lost, and eventually the mechanical counter jams altogether.

An ingenious device, the "scale-of-two" (invented by Wynn-Williams) transmits only every second pulse and has a very high resolution since it contains no moving parts, only radio valves. Usually several scales-of-two are arranged in cascade so that each transmits to the next one half of the pulses which it receives. Through this process of repeated halving the number of pulses with which the mechanical counter has to cope can be greatly reduced; if six scales-of-two are employed in cascade the mechanical counter has to record only every 64th of the original pulses and can therefore easily record many thousands of them per minute. A G-M counter needs about one ten-thousandth of a second to recover after each discharge, and if one does not want to lose more than a few per cent of the particles one should not count more than about ten thousand per minute. With ionization chambers even greater counting rates are feasible.

THE PHOTOGRAPHIC PLATE. If fast particles fall on a

photographic plate they produce (just as light does) a latent image which can be developed. Thus a large number of electrons, either falling on the plate or generated in it through the action of gamma rays, will affect the plate so that, after developing, it appears blackened. It was through this effect that Becquerel discovered radioactivity. The photographic plate is much less sensitive than a counter, but there are experiments where this does not matter and where one wants to know in which place the electrons strike the detecting instrument.

A single alpha particle entering a fine-grained emulsion can make several grains of silver bromide capable of being developed, and hence its trail can be identified later under a strong microscope, as a straight row of about a dozen black dots (silver grains). Thus the photographic plate can be used to make visible the tracks of alpha particles and other fast-moving nuclei. It does not give such fine details as the cloud chamber, and it does not make electrons visible, but it is very simple to use and has the advantage that it records particles all the time, in contrast to the cloud chamber, which records particles only during a short instant after each expansion.

**SUMMARY OF DETECTING TOOLS.** Most of the nuclear research work nowadays is done with counters or ionization chambers; mechanical counting devices are used to record the results. This method combines maximum sensitivity—since it will detect single atomic events—with the capacity—necessary to obtain accurate results—of recording a large number of events in a short time. Isolation of particles of a definite kind is usually possible. By adjusting the amplification, a proportional amplifier can be made to count protons in the presence of electrons, alpha particles in the presence of protons, fission fragments in the presence of alpha particles. On the other hand, a G-M counter will detect

electrons while heavier particles are absorbed in its wall, unless it is deliberately made very thin. When the particles are very plentiful they can be measured by an electroscope; this is also a kind of counting method, in the sense that weighing a bag full of coins is equivalent to counting them.

If a phenomenon is new and not yet understood it is often very difficult to unravel it by counting only. This is where the cloud chamber proves of the greatest value, since it shows at a glance the kind of particles involved and their interrelations. Had there been no cloud chamber, the discovery of the neutron, the positron and the meson would no doubt have been made, but later and with much greater effort. On the other hand, the accumulation of a sufficient number of data with a cloud chamber is slow and laborious. The chamber usually has to rest a few minutes after each expansion, and only a few tracks can be photographed each time, or else the picture gets too confused. After the pictures are taken each individual track has to be measured by a human observer. Therefore the cloud chamber is used for actual measurements (as distinct from orientation) *only* for phenomena which are hard to isolate by counting methods. In some cases the photographic plate can take the place of the cloud chamber; however, measuring the tracks under a high-power microscope is even more tedious than measuring cloud chamber tracks.

### *Attacking Tools*

IN ORDER to provoke a nuclear transformation one has to concentrate a large amount of energy on a nucleus. A rifle bullet has a vastly greater energy than an alpha particle, but its energy is distributed over a very large number of atoms and cannot be made to bear upon a single nucleus.

For this reason the bullets used in transforming nuclei

must themselves be of nuclear dimensions. Rutherford discovered the transformation of nitrogen nuclei under the impact of fast helium nuclei (alpha particles) which fortunately are supplied by natural radioactive substances. He realised that the scope of these investigations would be greatly enlarged if other light nuclei could be accelerated artificially to similar or even greater energies. It was under his direction that the first successful experiment of this kind was carried out by J. D. Cockcroft and E. T. S. Walton, the disintegration of lithium by fast protons.

The velocities which must be given to protons or other nuclei, to enable them to cause nuclear transformations, are measured in thousands of miles per second, vastly more than can be achieved by any known mechanical means, including explosives. The only way in which we can impart to them such large velocities is through the action of electric fields on their electric charge. The kinetic energy which a particle acquires on being accelerated is equal to the product of the charge and the electric potential difference between the points between which the acceleration takes place. It is therefore usual to express the energies of particles in units of one electron-volt (abbreviated ev) which is the energy of an electron (or a proton, since it carries the same amount of charge) which has been accelerated by a potential difference of one volt. For the purposes of nuclear physics this is a very small unit and a million ev—written one Mev—is a more appropriate unit. A proton with a kinetic energy of 1 Mev has a velocity of about 9,000 miles per second.

Only the lightest nuclei are suitable as bullets because heavier nuclei have a larger electric charge and are therefore more strongly repelled by the nuclei which we may want to hit. Most of the work has been done with protons (ordinary hydrogen nuclei), deuterons (nuclei of heavy hydrogen, the rare isotope with atomic weight 2, also

called deuterium), and alpha particles' (helium nuclei). In the description which follows of various methods of accelerating particles I shall speak of protons by way of example.

**HIGH-VOLTAGE ACCELERATION.** The straightforward way of producing protons with energies of, say, 1 Mev is to place protons at one end of an evacuated tube the ends of which are kept at a potential difference of one million volts. The electric field drives the protons along the tube with increasing speed until, at the other end, they hit the "target", a layer of the element the atoms of which we want to transform, or of one of its compounds.

The complete arrangement therefore consists of these four main parts: the ion source, where hydrogen is ionized in order to get protons; the acceleration tube in which the protons gather speed; the target where a few of them strike the nuclei which we want to study; and the high-voltage generator from which they derive their energy.

The ion source is built somewhat on the same lines as a radio valve. A hot filament emits electrons, which are drawn towards an anode by a potential of a few hundred volts. A slow stream of hydrogen gas is admitted so that some of the electrons on their way to the anode strike hydrogen molecules and ionize them. The ion source communicates with the accelerating tube through a small opening (say 1/8" diameter), and those ions which come close to this opening are sucked through by the strong electric field at the other side. If deuterons or helium nuclei are wanted, rather than protons, deuterium or helium is admitted instead of hydrogen.

The accelerating tube is usually made of a number of insulating sections (of glass or porcelain), separated by metal sections which are connected to the high-voltage generator in such a way that the electric potential increases

in equal steps from one section to the next. In this way each of the insulating sections has to carry only a fraction of the total potential, and experience shows that it is thereby possible to make the accelerating tube withstand much higher potentials than if it were just one long insulating tube. Several fast pumps (oil diffusion pumps) are attached to the tube to provide a good vacuum, constantly removing the small amounts of hydrogen which leak in from the ion source, along with the ions. A good vacuum is needed to prevent the protons from losing energy by collisions with gas molecules on their way along the tube; furthermore, if the vacuum gets poor, the gas in the tube becomes conducting and the generator is then no longer able to keep up the high electric potential required.

The target has to be cooled since the protons are brought to rest within it and their kinetic energy is converted into heat. Hence the target is often a hollow plate of copper through which water is circulated, covered with a layer of the element which we wish to bombard with protons. Only a thin layer is needed since even fairly fast protons cannot penetrate more than a millimetre of solid matter. The physicist speaks of a "thick target" if the layer is thick enough to stop the bombarding particles completely. In this case the protons lose their energy gradually on going through the material and may cause disintegrations at any time during this slowing down. If the experimenter wants to study the effect of protons of well-defined energy he uses a "thin target", by placing only a trace of the substance wanted onto the target plate, usually by distilling it on in a vacuum. In this thin layer the protons suffer very little loss of energy and the material below is chosen so that they do not cause nuclear transformations in it.

The most difficult task is the production of the necessary high voltage. If the potential difference between two pieces of metal is raised one comes eventually to a point where

the insulation of the air between them breaks down; a spark jumps from one piece to the other and the potential abruptly drops to a much lower value. In order to get higher voltages, one has to increase the distance between the two metal pieces; however, at one million volts a spark can traverse a distance of many feet. The resistance of air against electric breakdown can be enhanced several times by increasing its pressure and also by adding small amounts of certain other gases, in particular Freon (dichlorodifluoro-methane, commercially used in refrigeration plants).

Two types of high-voltage generators are at present in most common use: the transformer-rectifier set and the electrostatic belt generator (invented by Van de Graaff and usually called after him).

The transformer-rectifier set is a straightforward application of electrical engineering practice. Alternating current (as supplied by the power company) is converted, by means of a transformer, into a smaller current at higher voltage and is then passed through a rectifier valve (kenotron) which allows it to pass in one direction only. The current which has gone through the rectifier is a pulsating current and is smoothed with the help of large condensers. Every AC-operated radio receiver contains a similar unit for producing a DC-voltage of a few hundred volts, and the main difference lies in the necessity of using larger transformers, rectifiers, and condensers in order to get higher voltages. Since the transformer is the most expensive part and its price rises rapidly with its peak voltage, considerable ingenuity has been employed in the successful design of systems where the output voltage is several times larger than the peak voltage of the transformer used.

The "Van de Graaff" is a brilliant offspring of the ancient family of electrostatic machines, once the glory of the physicist's art, now mostly relegated to a dusty corner of

the lecture room. The fundamental principle of these machines is that electric charges can be carried bodily from one point to another by means of rotating discs, made of an insulating material. In the Van de Graaff the disc is replaced by an insulating belt travelling around two pulleys. Charge is sprayed onto the belt near one pulley and taken off to a large hollow metal sphere which surrounds the other pulley. As more and more charge accumulates on the metal sphere the potential rises until either a spark occurs or enough current leaks off the sphere to prevent the voltage from rising any further. For attaining voltages above a million volts, the whole arrangement (including the accelerating tube and ion source) is placed inside a large steel tank into which air (containing some freon) is pumped to a pressure of about 100 pounds per square inch. The target is usually placed at the end of a tube, several feet long, which protrudes from the steel tank in order to make the target easily accessible to whatever detecting tools are to be used (see fig. 7 and plate 6).

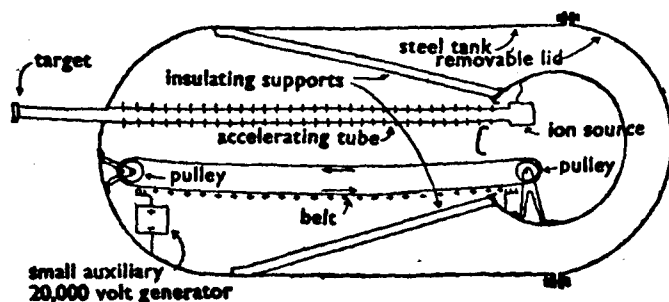


FIG. 7. BELT GENERATOR (VAN DE GRAAFF), WITH ACCELERATING TUBE, SCHEMATICAL

Transformer-kenotron sets have been built for voltages up to about two million volts, and with belt generators about four million volts have been reached. Further slow

progress along these lines is likely. In the meantime, several methods were discovered whereby it is possible to impart energies of many Mev to particles without actually generating such high voltages.

**MULTIPLE ACCELERATION; THE CYCLOTRON.** The first attempt of this kind was the linear multiple accelerator. A number of short metal tubes are lined up inside an evacuated container, with an ion source at one end; all the even tubes are connected together, and so are all the odd ones. If we were to place a constant potential difference between the two groups of tubes, for instance making the odd ones positive with respect to the even ones, a proton would be accelerated on passing from the first to the second tube, but would lose this extra energy again on passing from the second to the third tube. We can however use the time which the proton spends in the second tube to reverse the potential difference between the two tube systems so that the proton gets accelerated again as it enters the third tube, and this reversing process can be repeated for every tube in the system, so that the protons emerge with an energy which corresponds to the potential difference used multiplied by the number of tubes. To produce the required voltage reversals, the odd and even tubes are connected to a high-frequency generator (similar to a radio transmitter). The tubes are made longer and longer with increasing distance from the ion source, so that the ions spend the same time in each tube, despite their increasing velocity.

In order to get worthwhile energies one has to have a large number of tubes, and then the apparatus becomes impracticably long (hundreds of feet). The idea which made the method practicable was to put everything into a strong magnetic field, because in such a field the path of a freely moving charged particle is a circle rather than a straight

line. And here one very fortunate fact is of decisive importance: As the particle gets faster the circle on which it moves increases in size in just such a way that the time needed for a full revolution remains the same.

The instrument which was based on this idea soon became known under the name "cyclotron". Instead of a number of tubes, only two accelerating electrodes are needed which are called dees, for their similarity in shape with a capital "D". Together they form a hollow metallic "pill box", cut along one diameter. They are placed in an evacuated container, between the pole pieces of a very large electromagnet designed to produce a strong uniform magnetic field across them (see fig. 8). Ions are produced

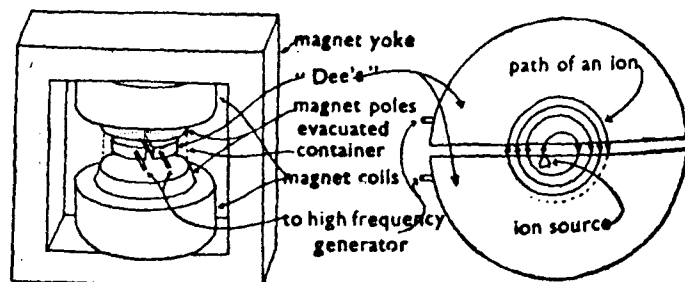


FIG. 8. CYCLOTRON, SCHEMATICAL

near the centre of the dees, with the help of an ion source somewhat similar to the one described earlier. Those ions which emerge from the source at the right time will be accelerated into one of the dees; after describing a semi-circle within it, the ion will get to the edge of the dee when the voltage (delivered to the dees from a high-frequency generator) has changed direction so that the ions get accelerated again. Of course the frequency of the field has to be carefully adjusted so that the ions keep in step with it. If this adjustment is achieved (largely by trial and error)

each ion will move on an expanding spiral, gaining energy every time it crosses the gap between the two dees, until it hits the edge of one dee. If one wants to utilize as many of the fast ions as possible one uses an "internal target" which intercepts the ions before they reach the edge of the dee; alternatively, it is possible to deflect part of the ions by means of strong electric fields and to guide them to a point outside the magnetic field where the target is more easily accessible.

By enlarging the magnet and the dees one can enable the ions to spiral out further and thus to gather more energy. For this reason, cyclotrons of ever-increasing size have been built in order to get particles of ever greater energies. The largest operating cyclotron has a magnet which weighs 200 tons, with pole pieces of 60 inches diameter; it can produce helium nuclei (alpha particles) of 40 Mev energy. A cyclotron with a 3,000 ton magnet having 184 inch poles has been designed to produce helium nuclei of upwards of 100 Mev, and there is little doubt that it will do so. However there is a limit to progress along these lines. The statement I made before, that an ion always needs the same time for a full revolution in a given magnetic field, independent of its velocity, is no longer strictly correct when the velocity of the particle becomes comparable with the velocity of light. When an alpha particle reaches an energy of 80 Mev the time for one full revolution has been lengthened by two per cent; very powerful high-frequency generators have to be used to complete the whole acceleration process in a fairly small number of revolutions, so that the particles do not get out of step before the acceleration is completed. Special tricks are needed, and are being developed, in order to push to appreciably higher energies (see plates 3, 4, 5).

Various schemes are at present under consideration by which it may be possible to produce particles with energies of several hundred Mev. The multiple linear accelerator

may stage a come-back, helped by the great progress that has been made, thanks to radiolocation, in the techniques of producing short electric waves of great intensity. We shall mention one instrument, the betatron, with which electrons (but not nuclei) of 100 Mev have actually been produced.

**THE INDUCTION ACCELERATOR ("BETATRON").** The betatron is an ingenious application of the principles on which the operation of a transformer depends. In a transformer, an alternating electric current is sent through a coil (the "primary") which surrounds an iron core. The oscillations in the magnetism of the core, caused by the oscillating primary current, produce an oscillating voltage in the "secondary" coil which also surrounds the iron core. This voltage is proportional to the number of turns in the secondary coil, and it is not difficult to build a transformer which will produce 100 volts per turn. A secondary coil containing a million turns would theoretically produce a voltage of one hundred million volts, but of course the insulation would break down long before such a voltage was reached.

In the betatron there is no secondary coil. Instead, there is a circular tube of glass or porcelain (shaped like the inner tube of a tyre) in which electrons are made to go round a large number of times. For each circuit the electron gains an amount of energy corresponding to the voltage produced in a single turn of an imaginary secondary coil, or about 100 volts, and it is actually possible to make the electrons go round approximately a million times. An appropriate portion of the magnetic field is diverted from the iron core so as to pass through the region in which the electrons are circulating, in order to bend their path (which would naturally be straight) to a circle of the desired size.

The betatron was invented in America during this war

(by D. W. Kerst, about 1941) and little use has been made of it for purposes of nuclear physics. Late in 1945, the General Electric Co., Schenectady, announced the successful operation of a betatron for making electrons of 100 Mev. This instrument is now being used for research and important results have been obtained with its help.

**NEUTRON PRODUCTION.** Neutrons do not occur in nature (except in very small numbers in the cosmic radiation) and if they did we could not accelerate them since they carry no electric charge. If we want neutrons we have to produce, with the help of protons or other charged particles, some nuclear transformations in which neutrons are liberated.

One way to do this is to bombard beryllium with alpha particles from a radioactive source. For instance, some radium salt is mixed with an excess of beryllium (both finely powdered) and enclosed in an airtight capsule (perhaps half an inch overall size). Such a source will emit the order of a million neutrons per second uniformly in all directions; it is easily fitted into any experimental setup, and practically unchanged with time. Nearly all the fundamental properties of neutrons were discovered with sources of this type.

The neutrons emitted from a radium-beryllium source are very heterogeneous, with kinetic energies varying between .1 and 10 Mev, approximately. By using artificially accelerated particles it is possible to produce homogeneous neutrons, that is, neutrons which have all very nearly the same energy. For instance, by bombarding deuterium with deuterons of .1 or .2 Mev (only a small transformer-kenotron set is needed) one gets neutrons of 2.5 Mev energy. A thin target of lithium, bombarded with protons of about 2 to 3 Mev (from a Van de Graaff) serves as a source of neutrons with energies which can be varied between almost zero and about 1 Mev, simply by varying the voltage of the

Van de Graaff. Very fast neutrons, and enormous numbers of them, are obtained by bombarding lithium with fast deuterons from a cyclotron.

The most powerful neutron source of all has recently come into existence through the realisation of nuclear chain reactions. The number of neutrons produced by a large graphite pile running at full power is millions of times greater than what can be obtained from a cyclotron. Even much smaller reactors could be used as very powerful neutron sources, and it is very likely that such reactors will soon find their place in nuclear physics laboratories.

Since neutrons are electrically neutral they are not repelled by the electric charge of atomic nuclei, and therefore can approach them even if they are quite slow. Some nuclei are even much more strongly affected by slow neutrons than by fast ones. Neutrons can be slowed down very easily by materials like water or paraffin wax which contain a lot of hydrogen. Each time a neutron collides with a hydrogen nucleus it loses, on an average, half its energy. After some twenty collisions its energy has become so low that it is comparable to the energy which the hydrogen atoms themselves have, on account of their heat motion (thermal agitation). After that, the neutron is just as likely to gain as to lose energy on colliding with a nucleus and it continues to wander aimlessly around in the material as a "thermal neutron" until it eventually combines with one of the nuclei present, or else escapes from the material.

#### *Auxiliary Techniques*

IN ADDITION to attacking tools—to cause nuclear transformations—and detecting tools—to detect the particles which result from those transformations—the nuclear physicist needs a number of techniques which serve to separate, out of a multitude of things which happen all at once, the particular phenomenon which he wants to

observe. Out of the large variety of such techniques, I shall describe a few of the more important ones.

**COLLIMATION.** Alpha particles are very easy to collimate, that is, to confine into a narrow beam; two small apertures cut into thin metal sheet or even paper will do the trick, one aperture being placed close to the source of particles, the other a little distance away. With electrons, the sheet has to be thicker, and furthermore, electrons tend to get deflected by collisions with air molecules, hence for good collimation the electron source and the collimating apertures have to be put into an evacuated container. Gamma rays can penetrate inches of solid lead; to collimate them, the source must be placed at the centre of a large lead block (say, a cube with sides a foot long) with a hole drilled from the surface to the centre. Neutrons can be collimated like gamma rays, only paraffin wax is used instead of lead, and an even greater thickness of material is needed (about two feet).

In many cases collimation can be achieved without the use of collimating apertures, simply by placing the detector at such a distance from the source that only particles within a narrow range of directions can hit the detector at all.

**ABSORBERS.** Alpha particles are completely stopped by a piece of paper. Mica can be split to produce sheets which are much thinner than paper and very uniform; the thickness of such a sheet can be found by weighing. If increasing thicknesses of mica are placed in a collimated beam of alpha particles of uniform energy the number which emerge remains unchanged at first, but drops to zero quite rapidly if the thickness of mica exceeds a certain amount; by measuring this amount one can find the energy of the alpha particles. If the alpha particles are a mixture

of particles with two different energies, the number recorded will drop to zero in two steps, as the thickness of mica is increased.

Electrons behave somewhat similarly, only the drop to zero is much more gradual. As a result, the use of absorbers (in this case usually thin sheets of aluminium) allows one to determine the greatest energy represented among the electrons in question, but gives only very vague indications concerning the presence of electrons of lower energy.

In the case of gamma rays—and even more so of neutrons—the use of absorbers is usually not the best way for energy determination.

**THE COINCIDENCE METHOD.** If an electron passes through two G-M counters it will produce a discharge in each, and the two discharges will be practically simultaneous. One can connect the two counters to a valve circuit which is made so that it will operate a mechanical counter if, and only if, both G-M counters discharge at the same time. Such a circuit is called a coincidence circuit.

One interesting application of a coincidence circuit is the following method for the determination of the energy of gamma rays. The gamma rays are allowed to fall on a thin metal foil; most of the gamma quanta go through but some of them eject electrons from the foil. If one now tries to determine the maximum energy of these electrons (which is equal to the energy of the gamma quanta) by measuring their absorption in metal foils, as mentioned before, the absorption effect will be partly masked by the fact that, as we increase the thickness of the absorber, additional electrons are ejected from the absorber by the gamma rays. However if the original electrons are recorded by two G-M counters connected to a coincidence circuit, and the absorber foils are placed between the two counters,

then the additional electrons will pass only through one of the two counters and will therefore not be recorded, and the absorption of the electrons ejected from the first metal foil can be determined correctly.

Other applications of coincidence circuits are the investigation of nuclear reactions which result in the simultaneous emission of two particles from the same nucleus. It is also possible to connect more than two, that is, three, four or more G-M counters to the same coincidence circuit and thus to select, for instance, electrons, travelling in a given direction, which have been emitted simultaneously with two gamma quanta, without being disturbed by the presence of numerous other electrons and gamma quanta which do not fulfil this special condition. It is easily seen that the coincidence method is indeed a very powerful and versatile tool for disentangling nuclear phenomena.

**NEUTRON DETECTION.** Fast neutrons are detected usually by their capacity to collide with hydrogen nuclei and to transfer part of their energy to them; the fast protons which result can be detected with an ionization chamber connected to an amplifier. For this purpose, the ionization chamber is either filled with hydrogen or lined with a thin layer of a hydrogenous compound such as paraffin wax. Slow neutrons, in particular thermal ones, have too little energy to be detected in this way. Here one can make use of the fact that boron nuclei are very readily transformed by slow neutrons, under emission of fast alpha particles which are easily detected. The "boron chamber", an ionization chamber lined with boron or else filled with gaseous boron trifluoride, is a very convenient and widely used instrument for measuring the intensity of a stream of slow neutrons.

An entirely different method depends on the fact that certain elements (gold, iodine, manganese and many others)

become radioactive under the action of slow neutrons. This activity can be measured with a G-M counter or, if it is strong enough, with an electroscop.

**DECAY CURVES.** Many nuclear reactions result in the formation of a nucleus which is unstable and tends to disintegrate spontaneously after some time, in most cases with the emission of a (positive or negative) electron. For instance, if sodium is exposed to slow neutrons some of the neutrons are captured by sodium nuclei, resulting in the production of sodium with the atomic weight 24 (ordinary sodium has 23). If a sample of this irradiated sodium is placed near a G-M counter one finds that the counting rate due to the sample decreases with time in a quite defined fashion. If the rate decreases by a certain factor during the first hour it will decrease by the same factor during the second hour, or indeed during any hour, and the same statement is true if, instead of one hour, some other time interval is chosen. It is usual to characterise the rate at which a given radioactive substance decays by indicating the so-called half-life, that is, the time interval in which the counting rate drops to one half. The half-life of sodium 24 is 15.5 hours; hence in  $2 \times 15.5 = 31$  hours the counting rate drops by a factor 4, in  $3 \times 15.5 = 46.5$  hours by a factor 8, and so on.

At this point it is convenient to consider the logarithm of the counting rate. If a number decreases by a certain factor its logarithm decreases by a certain amount. Hence the logarithm of the counting rate, in our example, decreases by a constant amount every hour. If we make a graphical representation of the logarithm of the counting rate as a function of time (just as a business manager represents the varying rate of sales by a curve) we get a curve which descends with a constant slope; in other words, a straight line.

From the slope of this line, the half-life can be obtained at a glance, and the fact that the line is indeed straight assures the experimenter that he is dealing with a pure radioactive sample. If his sample contains a mixture of two or more active isotopes the line will no longer be straight. For instance, if sodium is irradiated with fast, rather than slow, neutrons the activity of the sample is found to drop very rapidly for the first minute or so, then more slowly during the next half hour, and finally at a slow rate corresponding again to a half-life of 15.5 hours. If the logarithm of the counting rate is plotted against time as before one obtains a curved line (fig. 9). This line can be shown to be a

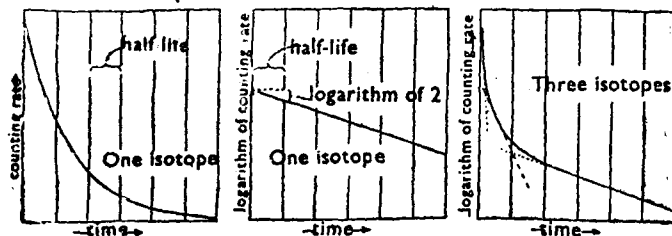


FIG. 9. DECAY CURVES

“superposition” of three straight lines; in other words, the sample contains a mixture of three active isotopes, the half-lives of which turn out to be 40 seconds, 10 minutes and 15.5 hours. If more than three or four radioactive isotopes are present in a sample, and in particular if their half-lives are not widely different (as they fortunately are in the case of sodium) this analysis of the decay curve becomes very unreliable, and the chemist must be called in to help.

**CHEMICAL SEPARATION.** In most cases the radioactive substances which result from the bombardment of a

certain element are not all isotopes of the same element and can therefore be separated by chemical methods. One may for instance dissolve the sample and then add some reagent which will precipitate one of the elements in question but not the others. One peculiar difficulty lies in the fact that although the reagent may form an insoluble compound with the element which we want to separate, so little of it is usually created in the nuclear transformation that no solid grains can be formed which are big enough to be held back on a filter, and hence no precipitate is formed which can be filtered off. One therefore usually adds to the solution a small amount of the element which one is trying to separate, so that a precipitate may be formed. This so-called carrier is ordinary, non-radioactive material and therefore does not disturb the radioactive measurements.

The transformation of uranium by neutrons, which forms the basis of atomic power, is such a complex superposition of different processes that for about three years it frustrated the efforts of scientists in Rome, Paris and Berlin. Clues to the right answer accumulated but were not recognised. Following one of these clues, Hahn and Strassmann in Berlin fixed their attention on a certain active substance which resulted from the bombardment of uranium with neutrons, and which could be precipitated with barium as a carrier. This fact did not yet prove that the substance in question was an isotope of barium, for radium behaves similarly. The crucial experiment was the attempt to separate the unknown substance from its barium carrier, an attempt which was unsuccessful while a small amount of a known radium isotope which had deliberately been added was indeed separated from the barium carrier. This experiment proved conclusively that the unknown active product was an isotope not of radium but of barium. Since the barium nucleus has less than two-thirds of the charge

of the uranium nucleus, the conclusion that the uranium nucleus, on impact of a neutron, may break into two pieces of comparable size had become unavoidable and was indeed soon confirmed by physical experiments. It was soon found that it is not so that one of the fragments is always a barium nucleus; the uranium nucleus can break in a variety of ways, and isotopes of more than twenty elements have been found among the products of nuclear fission.

## ABOUT OUR CONTRIBUTORS

**H. L. ANDERSON.** Received his Doctor's Degree in Physics at Columbia University in 1940. Started to work on the atomic energy problem as an Assistant to Dr. Enrico Fermi at Columbia in 1939, and continued the work there until it was transferred to Chicago at the Metallurgical Laboratory in 1942. At Chicago took part in the construction and operation of the first two chain reacting piles and also in the design of the piles constructed at Hanford, Washington, for the production of plutonium. Spent the year 1945 at the Los Alamos Laboratory and took part in the testing of the first atomic bomb in New Mexico. At present is Assistant Professor of Physics, Institute for Nuclear Studies, University of Chicago.

**MRS. MARY LANGS ARGO.** Born in Detroit, Michigan. Received her B.A. degree in 1939 from the University of Washington in Seattle; M.A. degree in 1941 from Mills College, Oakland, California, and then went to the George Washington University (1941-43) as an instructor in Physics. Worked for the Manhattan Project at Los Alamos, New Mexico, from 1944 to 1946 and was in the group headed by Dr. Teller. Is at present working for the Metallurgical Laboratory (part of the Manhattan District) at the University of Chicago.

**HANS A. BETHE.** Born in Strasbourg in 1906 and educated at Frankfurt and Munich Universities, receiving his Ph.D. in Physics in the latter in 1928. Held various positions in German universities from 1928 to 1933. Came to England in 1933 (Universities of Manchester and Bristol). Professor of Physics at Cornell University, Ithaca, New York, since 1935.

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**OTTO ROBERT FRISCH, O.B.E.** Born in Vienna in 1904. Studied at Vienna University, receiving Ph.D. degree in 1926. Occupied in research at Berlin (1927-30), Hamburg (1930-33), London (1933-34) and Copenhagen (1934-39). Joined the atomic bomb project in Liverpool in 1940 and later went to the bomb research establishment at Los Alamos to continue this work (1943-46). Recently returned to this country to head the Nuclear Physics Division of the Government Establishment for Research on Atomic Energy at Harwell. Co-author (with Prof. Lise Meitner) of the paper in which the term "nuclear fission" occurs for the first time, and the first to demonstrate experimentally the enormous energy liberated by the fission of a uranium nucleus.

**PHILIP MORRISON.** Assistant Professor of Physics at Cornell University, closely associated with the atomic bomb project. Was a physicist at the Metallurgical Laboratory at the University of Chicago and is now at the Los Alamos Laboratory in New Mexico. Member of the group which carried out the test shot of the bomb; in July, 1945, was in Japan with the group which investigated the damage of the atomic bombs and which examined the position of atomic research in Japan. Professor Morrison received his B.S. degree from the Carnegie Institute of Technology and his Ph.D. degree from the University of California in 1940. Before the war he was connected with the physics

department of the University of Illinois, and has recently joined the faculty of Cornell University.

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*The reader will usually find the most convenient explanation of a term on that page quoted here which is within the article he is reading. Where there is no reference to the same article or where a fuller explanation is wanted, he should turn to the page given in bold type.*

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