Radioactivity and Atomic Theory.

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NEARLY forty years have passed since the spontaneous radioactivity of uranium was shown by Becquerel in 1896. We know that the investigations which led to this fundamental discovery were much influenced by the discovery of *X*-rays by Röntgen in the preceding year. We can now look back with some sense of perspective and recognise the extraordinary importance of the discovery of radioactivity and the profound influence on our knowledge of atoms and the relation of the elements which has followed from a detailed study of the radioactive bodies.

In the course of this lecture, I have thought it of interest to give a brief account of some of the earlier experiments in radioactivity which pointed the way to the conclusion that the radioactive bodies were undergoing spontaneous transformation. This will be followed by a statement of the most significant of the discoveries that have resulted from an examination of the chemical and radioactive properties of the radio-elements. But this in a sense is only the beginning of the story. The use of swift α-particles to bombard matter gave us the first proof that certain light elements could be transformed by artificial methods. This has been followed in recent years by experiments in which streams of other fast particles, like protons, neutrons, and deuterons, have been artificially generated in order to bombard matter. By these methods, we have been enabled to extend widely our knowledge of the modes of transformation of the elements. In some cases, the nuclei of the atoms can be caused to break up with explosive violence, giving rise to new stable elements. In other cases, new radioactive bodies are produced which correspond to unstable isotopes of the elements. More than 50 of these artificially produced radioactive bodies are now known, and no doubt many more will be found in the near future.

The subject of radioactivity has indeed been born anew and has entered again on a new and vigorous phase of life. It is of interest to note that the methods developed long ago for the investigation of the radioactive bodies proper are now every day being applied to study the artificial transformation of elements and to follow the chemical changes involved. I have personally followed with great interest this ever-widening extension of the province of radioactivity, which to-day embraces so many workers and has already given us a new science in which the reactions occurring in the minute nucleus of an atom can be studied. The opening up of this new territory has only been made possible by the development of new and powerful electric methods of producing intense streams of bombarding particles with high speeds, and by the improvement of the automatic methods of counting swift particles and by the wide use of that wonderful instrument, the Wilson expansion chamber, to obtain visual evidence of the process of transformation.

Before discussing the changes in our ideas due to the study of radioactive transformations, we may pause for a moment to consider the prevailing ideas on atoms and their structure just before the discovery of radioactivity (1896), and the proof of the independent existence of the electron (1897). The atomic theory of Dalton had been almost universally accepted as the basis of the interpretation of the facts of chemistry. The work of the chemist for nearly a century had resolved our material world into 80 or more distinct types of atoms or elements, and had shown that the atoms of the elements were stable entities unchangeable by the chemical and physical forces then at our disposal. With increase of knowledge, the old ideas of the alchemists of the transmutation of the elements had been discarded, although it was recognised that one of the main problems of chemistry was to disclose the true relation of the elements and if possible to devise more potent methods capable of changing one element into another. This was well expressed by Faraday, " to decompose the metals, then, to reform them, to change them from one to another, and to realize the once absurd notion of transmutation, are the problems now given to the chemist for solution." To the philosophic mind, the periodic law of Mendeléef was of great significance in indicating that the atoms of the elements were not separate creations but closely related in their ultimate structure, but there was at that time no clue to the underlying meaning of this remarkable relation. It should be recalled that the periodic classification had been successful in predicting the properties of missing elements, and indeed, the position of several elements discovered later, after Moseley's generalisation, had been indicated correctly.

While the law of combining proportions did not involve any definite knowledge of the size and structure of atoms, yet the size and weight of the individual atoms had been roughly estimated from data based on the kinetic theory of gases. There was, however, little definite information to form any idea of the structure of atoms, although theoretical physicists like Larmor and Lorentz, in order to account for the vibrating properties of the atom as shown by its line spectrum, had suggested that the atom must consist of charged particles, but there was no evidence of the nature of the particles concerned. This difficulty, as we now know, was in part resolved by the discovery of the electron and the interpretation of the Zeeman effect. At this stage, although the relative atomic weights of many of the elements had been accurately measured, the ideas of atoms were very vague and uncertain. Although an enormous amount of information on the combining properties of atoms had been collected, and simple and useful working rules had been applied in explanation, more definite ideas of the underlying meaning of chemical combination had to await a much clearer conception of the electronic structure of atoms.

Early Experiments in Radioactivity.

My introduction to the subject of radioactivity began in a natural way in the Cavendish Laboratory, Cambridge, in 1897 as the result of earlier experiments on the ionisation produced in gases by X-rays. Becquerel had shown that the radiation from uranium caused the discharge of an electroscope, but had concluded that the radiation was different from X-rays in showing some evidences of refraction and polarisation. I proceeded to examine whether the ionisation was of the same type as that produced by X-rays and in the course of the work found that the rays were of two types, one easily absorbed, called the α-rays, and a more penetrating type, named the β-rays. A few observations were also made on the rays from thorium, which Schmidt in 1898 had found to be radioactive. Soon after my appointment to McGill University, Montreal, in 1898, Professor R. B. Owens and I began some experiments on the radiations from thorium, using the electrical method. We found that the effects produced by some thorium compounds, and particularly the oxide, appeared to be very capricious and much influenced by slight draughts of air in the testing vessel. Strong ionising effects were observed when thoria was covered with several sheets of paper, but only weak effects when the preparation was completely covered over by a thin sheet of mica. This peculiar inconsistency of the effects from thorium was at first very puzzling, as under the same conditions the radioactivity shown by uranium was quite constant.

In order to investigate the matter further, I arranged to pass a current of air over the thoria down a long tube and to examine the conductivity of the air in a large ionisation chamber by means of an electrometer. I then found that, on stopping the current of air, the ionisation effect fell off according to a geometrical law with the time, diminishing to half-value in about 1 minute. It thus seemed clear that thoria emitted some kind of active substance which was carried away with the air stream and decayed in activity with time. I gave the name " Emanation " to this unknown substance which readily diffused through paper. This was the first time that the characteristic law of decay of radioactive bodies had been measured. At the same time, I noticed that all substances which came in contact with the emanation for some time became radioactive. This " excited " activity, as it was unfortunately termed, decayed with time after the removal of the emanation, according to the same law as the emanation but with a much longer half period, *viz.*, 4 hours instead of one minute. Another surprising result was observed in a strong electric field. The activity was to a large extent concentrated on the negative electrode. In this way, a platinum wire could be made strongly active. The activity on the wire could be driven off by heat and removed by solution in acids, but when the acid was evaporated, the activity remained behind. These results were a strong indication that the activity was due to some kind of matter produced either from the emanation or by its action. It seemed likely that the emanation existed in very minute quantity, but it occurred to me that diffusion methods might throw light on whether the emanation was a light or a heavy substance. For this purpose, the relatively long-lived emanation from radium was employed. By measuring the coefficient of diffusion of the emanation into air, Miss H. T. Brooks and I concluded that its molecular weight was large and of the order of 100.

About this time, 1901, began that fruitful association with F. Soddy, who was then a teacher in the Chemical Department of McGill University. At this stage, the subject of radioactivity was in a very confused state. A number of substances had been found to show a temporary activity when separated from a radioactive solution or exposed to radioactive bodies, and the idea had arisen that the radiations had in some way the property of " inducing " radioactivity on bodies exposed to the radiation. This was a natural but mistaken idea which had to be cleared away before progress could be made. For this purpose we first made experiments on the thorium emanation to determine its chemical properties and to find whether it originated from thorium itself or from some other substance associated with it. We found that a new radioactive substance, named thorium-X, could be chemically separated from thorium and that this substance and not thorium itself gave rise to the emanation. It was found that thorium-X was being produced at a constant rate in the thorium and was converted into emanation. The constant activity due to thorium-X was shown to be the result of an equilibrium process in which the decay of the active matter was balanced by its continuous production. This process of production and decay was found to be a universal property of the radioactive bodies.

A study of the chemical properties showed that the emanation of both thorium and radium must be chemically inert and correspond to the group of gases of the helium–argon family. We now know that the radioactive emanations are isotopic representatives of the last of the inert gases. Finally, the material nature of the emanations was definitely established by proving they could be condensed in a spiral surrounded by liquid air. It is a noteworthy example of the delicacy and certainty of the methods of detection of radioactive matter that the chemical nature of the emanations and their condensation at low temperatures could be definitely established with almost infinitesimal amounts of active matter, far too small to be seen or weighed or detected by the spectroscope.

The experiments with thorium-X and the emanation gave us for the first time a clear idea of radioactive processes and led us to put forward in 1902—1903 the transformation theory of radioactive elements. Although the results were substantiated and extended by investigations with other radioactive substances, time does not allow me to refer to them, and I must pass on at once to consider the importance of these new ideas on transformation.

The Transformation of Radio-elements.

The proofs that radioactivity was a sign and measure of the instability of atoms and that the radio-elements were undergoing spontaneous transmutation were contributions to our knowledge of outstanding importance. The long series of radioactive changes in uranium, thorium, and actinium were with few exceptions made clear during the next few years. There were thus brought to light more than 30 radio-elements, each of which showed distinctive radioactive behaviour and broke up according to a simple and definite law. In most cases, in the process of transformation, the radio-element emitted either a swift α-particle, now known to be a charged atom of helium, or a fast β-particle (negative electron). The transformation process is distinguished from an ordinary chemical reaction, not only because the disintegration appears to be spontaneous and unalterable by the forces at our command, but, most important of all, by the enormous amount of energy emitted from each exploding atom. This energy is for the most part emitted in the kinetic form of a swift α- or β-particle, but in some cases a part of the energy is emitted in the form of electromagnetic radiation of high frequency (γ-rays). Since there was a large emission of energy in the change of one atom into another, it was natural to infer that a large store of energy was contained in a heavy atom. It was clear, too, that the atom must be the seat of intense internal forces in order to be able to hurl out a fragment of itself with such high speed.

Since experiments are usually made with small quantities of active matter or with elements like radium of slow rate of transformation, it is not easy to realise except in imagination the extraordinary effects that would be observed if we could, for example, experiment with a reasonable quantity of a short-lived element like the gas radon. Suppose we were able to obtain a kilogram of this gas and introduce it into a bomb made of heat-resisting material. At the end of about 2 hours, heat would be evolved corresponding to about 20,000 kilowatts and the bomb would be melted unless it were very efficiently cooled. Penetrating γ-rays would be emitted with energy corresponding to about 1,000 kilowatts. The heating effect would die away with the decay of radon (half period 3·8 days). At the end of about 2 months the radon would mostly have disappeared, but in its place would remain about 54 grams of the gas helium, and deposited on the walls 946 grams of a lead isotope (radium-*D*, atomic weight 210), mixed with a small quantity of radium-*E* and polonium. After allowing about 200 years for most of the radium-*D* to disappear, we should then find remaining about 72 grams of helium and 928 grams of an inactive lead isotope of atomic weight 206. I cannot imagine a more convincing experiment to illustrate the striking nature of these radioactive transformations, but unfortunately, or rather fortunately having regard to the safety of the investigator from the radiations, there is little chance of trying such a large-scale experiment.

The property of radioactivity, apart from uranium and thorium and their products, is shown only by a few other elements, potassium, rubidium—to which may now be added samarium—and then only to a very feeble degree. All the rest of the chemical elements appear to be permanently stable when tested by the criterion of radioactivity.

When once the nature of the α- and β-particles had been established and the long series of radioactive changes in uranium, thorium, and actinium had been mostly made clear, it appeared that the main contribution of radioactivity to our knowledge was nearing an end. But it is characteristic of this subject that no sooner does it appear to be visibly moribund than it flashes out again into vigorous life, leading to new and unexpected additions to our knowledge. This is well illustrated by the work of the next few years, 1911—1913, which saw three new advances of great significance for the future—I refer to the idea of the nuclear structure of atoms, the conception of the isotopic constitution of the elements, and the proof of an extraordinarily simple relation between the chemical properties of the radio-elements known under the name of the " Displacement Law."

The discovery of the electron in 1897 and the proof that it was a constituent of all atoms gave a great impetus to the belief that atoms were electrical structures. In 1904, Sir J. J. Thomson had proposed his well-known model atom and devised methods for estimating the number of electrons contained in each atom. On account of its mass and great energy of motion, the α-particle offered great advantages as a projectile to investigate the inner structure of atoms. It was known that it travelled through matter in nearly a straight line and must penetrate freely the structure of the atoms in its path. In addition, the scintillation method provided a delicate means of counting individual α-particles. The proof that the α-particle occasionally suffered a deflection through a large angle as the result of a single collision provided clear evidence that enormous deflecting forces existed within the atom. From these observations, I was led in 1911 to the idea that the atom was a very open electronic structure containing at its centre a very minute charged nucleus in which most of the mass of the atom was concentrated. The properties of the atom were defined by an integer representing the number of units of resultant charge carried by the nucleus. The fine experiments of Geiger and Marsden gave convincing evidence of the accuracy of the laws of scattering of α-particles calculated on this hypothesis and also gave us approximate estimates of the nuclear charge of the elements. As you know, this conception that the properties of the atom are defined by an integral number was verified and extended by the splendid experiments of Moseley on the *X*-ray spectra of the elements. He showed that the properties of an atom depended on its ordinal number, and identified this with the nuclear charge—a result later substantiated by Chadwick by direct determination of the nuclear charge by scattering experiments. Moseley's work was of far-reaching importance, for it fixed once for all the number of the elements between hydrogen and uranium and gave the atomic number and *X*-ray spectra of the missing elements, several of which have since been discovered.

The next two important discoveries were a direct consequence of a very careful study of the chemical properties of the radio-elements. Several observers had noted that it was impossible chemically to separate certain radioactive elements when mixed together, for example, thorium and ionium, radium-*D* and lead, radium and mesothorium, although these elements showed quite distinctive radioactive properties and were believed to be of different atomic weights. Soddy concluded that these elements of identical chemical properties must occupy the same place in the periodic table, and gave them the name of " isotopes." This was the first time that proof had been obtained that an element might be complex and consist of atoms differing in mass and structure. The complexity of the radio-elements is now well established. The three well-known radioactive series contain, for example, 6 isotopes of thorium, 3 of radium, 7 of lead, and 7 of polonium, and each of these isotopes shows a different mass and distinctive radioactive behaviour.

The next notable advance was the proof that the position of a radio-element in the periodic table had a very simple connexion with the type of radiation emitted by the parent product. Soddy had early noted several cases in which the emission of an α-particle, which carries two units of positive charge, gave rise to a product which had the chemical properties of an element two places preceding its parent in the periodic table. We now know that the effect of an emission of a β-particle, which carries only one unit of negative charge, is a corresponding displacement of one group in the opposite direction. The more complete generalisation had to await a more definite knowledge of the chemical nature of some of the products, much of which was supplied by the careful work of Fleck. The essential features of this process, known as the displacement law, were put forward about the same time in 1913 by Fajans, by A. S. Russell, and by Soddy, and not only included within their scope nearly all the radioactive bodies in the three main families, but even predicted the properties and positions of elements hitherto unobserved. The proof of this relation indicated that the periodic grouping of the elements was closely connected with the loss or gain of charge of the atom due to the expulsion of an α- or β-particle.

While the displacement law, as put forward, is quite independent of any special theory of the atom, yet we see that it is in complete accord with the nuclear theory if we suppose that the α- and the β-particle are released from the nucleus. The atomic number and atomic weights of uranium and thorium being known, the atomic number and weight of each of the successive elements can be written down from a knowledge of the radiations emitted by each element—illustrating the extraordinary simplicity of the laws which hold for atomic nuclei.

The new conception of the isotopic constitution of the radio-elements naturally had a great influence in promoting experiments to decide whether the ordinary inactive elements also were complex. Very largely owing to the pioneer work of Aston, the broad features of the isotopic constitution of the great majority of the elements were soon established, indicating that the varieties of stable atoms were much more numerous than had been supposed.

Artificial Transmutation.

We now come to a discovery, the proof of the artificial transmutation of the elements, which has led to a wide extension of the field of radioactivity. A few words should first be said of the theoretical aspects of this problem as they appeared to me in 1918. On the nuclear theory, an atom could only be changed by altering in some way the charge or mass of the nucleus, or both together. It was known that the nucleus was of exceedingly minute dimensions with a radius of the order 10^{-12} cm. and must be held together by exceedingly powerful forces in order to prevent its spontaneous disruption. In order to transform an atom, it thus seemed clear that a very concentrated source of energy must be brought to bear on the individual nucleus. Actuated by these ideas, I began experiments in 1918 to test whether the bombardment of light elements by energetic α-particles might lead to the occasional transformation of a nucleus as the consequence of a direct collision between the nuclei concerned. It could be calculated that in such an encounter the α-particle must come very close to the nucleus, even if it did not penetrate its structure. Such a close approach must in any case give rise to enormous forces between the α-particle and the nucleus which might be expected to produce such a distortion of its structure as to result in the disintegration of the nucleus. The scintillation method was employed to detect whether any fast particles appeared under such an intense α-particle bombardment. No effect was noticed for carbon or oxygen, but a number of fast particles were observed in the case of nitrogen, which were identified as swift hydrogen nuclei, now known as protons. It seemed clear that these protons could only arise as the result of the transformation of the nitrogen nucleus. In the light of later results, the essential processes involved in this transformation are now clear. Occasionally an α-particle actually enters the nitrogen nucleus and forms a new atom like fluorine of mass 18 and nuclear charge 9. This new nucleus is unstable and instantly breaks up with explosive violence, hurling out a fast proton and leaving behind a stable nucleus corresponding to a stable isotope of oxygen of mass 17. On an average only one α-particle in 100,000 is effective in producing such a transformation.

With the help of Chadwick, it was soon found that 12 of the light elements could be transformed in a similar way with the emission in each case of protons, but with different speeds and numbers. Time does not allow me to discuss later important developments which have shown that groups of protons of different velocities are ejected from each element and which have proved that resonance levels exist within the struck nucleus favouring the capture of α-particles of definite speed. Further investigation led to a discovery by Chadwick in 1933 of great significance. The element beryllium when bombarded by α-particles does not emit protons but a new type of particle of mass about 1 and zero charge called the "neutron." This new particle has remarkable properties, since, owing to its absence of charge, it can pass freely through the structure of atoms. Occasionally, it collides elastically with a nucleus, which is set in swift motion, but sometimes it enters a nucleus and is captured by it. The marked efficiency of the neutron in producing transformations in nitrogen, oxygen, and other light elements was early shown by the experiments of Feather and Harkins, and, as we shall see, has led to very wide developments in the last two years. Before, however, discussing these advances, I must refer to another discovery of outstanding importance made by M. and Mme. Curie-Joliot in 1933, in which they showed for the first time that veritable radioactive bodies could be artificially created by the bombardment of certain elements by α-particles. Before this observation, it had been supposed that a stable element or elements were always produced as the result of the atomic explosion. They observed that when boron was bombarded by α-particles, an unstable element was produced which broke up with the emission of fast positive electrons and behaved exactly like a radioactive body of half period 10 minutes. This radioactive body had the chemical properties of nitrogen and the scheme of transformation as given below:

$$ {}^{10}_{5}\mathrm{B} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{13}_{7}\mathrm{N} + \text{neutron} $$

$$ \text{and } {}^{13}_{7}\mathrm{N} \longrightarrow {}^{13}_{6}\mathrm{C} + \text{positron} $$

Similarly they found that bombardment of aluminium gave rise to radio-phosphorus of half period 3·2 minutes, which also broke up with the emission of positrons. The formation of radioactive bodies in this way is of great interest, and the appearance of the positron in these transformations is very unexpected.

It was soon shown that artificial radioactive bodies could be produced in various elements not only by bombardment with α-particles but also by protons, neutrons, and deuterons. In particular, Fermi and his collaborators showed that neutrons were exceedingly effective in producing radioactive bodies by bombarding the heavier elements, and more than 50 of these radioactive bodies were soon discovered, each with a characteristic period of decay. In contrast to the radioactive bodies produced by the α-rays in light elements, in the case of the heavier elements, the radioactive body emitted during the transformation not positive but negative electrons. In a number of cases, the chemical properties of the radioactive body have been determined and the scheme of transformation made clear, but obviously time will be required to make sure of the process of transformations in elements which consist of a number of isotopes.

Fermi made another observation of great interest when he found that in the case of some elements, slow neutrons were much more effective in producing transformations than fast ones. Slow neutrons can be readily produced by passing the fast neutrons formed in a transformation through a considerable thickness of hydrogen-containing material, for example, water or paraffin. This aspect of the problem is now under intensive investigation throughout the world, and certain general conclusions have been reached. For fast neutrons, the cross-section of the atom for capture of the neutron varies somewhat from element to element, but is of the order 10^{-24} cm.^{2}. For slow neutrons, however, the cross-section for capture for some elements may be from 100 to 10,000 times greater than for fast neutrons. For example, cadmium and boron readily absorb slow neutrons and a still stronger absorption is shown by europium and gadolinium. So marked is the effect of the latter that a layer a small fraction of a millimetre thick is almost a complete absorber for slow neutrons. It is natural to suppose that absorption of the neutrons in an element is a sign of its transformation, even though it may not be easy to obtain proof of the exact nature of the transformation. There is now clear evidence, as shown by Moon and others, that some of the slow neutrons which are effective have thermal velocities. Still more remarkable, absorption in some elements seems to take place over a small range of velocities, a result which may indicate that there are very low energy resonance levels in some nuclei.

The ease with which slow neutrons are able to enter the nucleus of even the heaviest elements has proved of great service. The use of the neutron as a projectile has disclosed the existence of 50 or more ephemeral elements of the radioactive type, representing unstable varieties of isotopes of the elements, and has thus much extended our knowledge of atomic species. Most of these unstable atoms appear to be transformed directly into a stable atom, but in the case of the heavier elements it is quite likely we may be able to produce radioactive atoms which may break up in a succession of stages like the atoms of uranium and thorium. M. and Mme. Joliot-Curie conclude that a radioactive element of this type is formed by the action of slow neutrons on thorium, but the evidence is yet not complete. It will be a matter of great interest if we are able to create in this way new radioactive families for study.

My time is too limited to discuss with any detail the large number of new types of transformation which can be brought about by using fast protons and deuterons as projectiles. In some cases, the element formed by the capture of the incident particle breaks up into fragments; in others, a new stable element is formed, and in others a radioactive element. The use of deuterons as projectiles has disclosed many new and interesting types of transformation, in which either a proton or a neutron is released. One of the simplest and most striking of these transformations is produced when deuterium is bombarded by its own ions. Oliphant and others have shown that two distinct types of transformation occur :

$$
\begin{aligned}
{}^2_1\mathrm{D} + {}^2_1\mathrm{D} &\longrightarrow {}^1_1\mathrm{H} + {}^3_1\mathrm{H} \\
\text{or} &\longrightarrow {}^1_0n + {}^3_2\mathrm{He}
\end{aligned}
$$

In one case, a fast proton and an isotope of hydrogen of mass 3 appear; in the other, a fast neutron and an isotope of helium of mass 3. The masses of these hitherto unknown isotopes can be deduced with confidence from a consideration of the energy changes. Both of these isotopes are believed to be stable. While ^{2}H and ^{3}H and ^{3}He appear in several other transformations, no certain evidence has so far been obtained of the isotope of helium ^{5}He. A stable isotope of beryllium of mass 8 is also formed in certain transformations as well as radioactive isotopes. It is worthy of note that apart from the mass 5, all the masses from 1 to 20 on the atomic scale are represented either by stable or by radioactive atoms.

Conservation of Energy in Transformations.

In the transformation of the light elements by bombarding particles, the energy released per atom is of the same order of magnitude as that observed in the radioactive bodies. In a few cases, particularly when deuterons are employed, the release of energy is considerably greater, and α-particles are expelled with higher speeds than from the radio-elements. In some cases too, penetrating γ-rays are emitted of high quantum energy. For example, the bombardment of ^{7}Li by protons gives rise to intense γ-rays of quantum energy as high as 16 million electron-volts—five times greater than the most penetrating γ-rays from radioactive bodies.

It is in general believed that the principle of the conservation of energy holds in these nuclear reactions when account is taken of the change of mass in the system before and after transformation. The equivalence of mass and energy seems now well established. A decrease of mass dm of a system corresponds to an emission of energy c^2dm, where c is the velocity of light. This law of equivalence is well illustrated in the transformation of the lithium isotopes by protons and deuterons shown below :

$$^7\text{Li} + {}^1\text{H} \longrightarrow {}^4\text{He} + {}^4\text{He} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$^6\text{Li} + {}^2\text{D} \longrightarrow {}^4\text{He} + {}^4\text{He} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The relative masses of the nuclei involved are known from the accurate measurements of Aston and Bainbridge by the mass-spectrograph. The difference between the masses on the left- and the right-hand side of equation (1) is 0·0181 on the atomic scale, corresponding to a change of energy of 17·1 million electron-volts. This is in close accord with the accurate measurements of Oliphant and others of the energy of the expelled α-particles, *viz.*, 17·1 million volts. Similarly, kinetic energies of the α-particles liberated in equation (2) are 22·5 million volts, and this is found to agree well with the change of mass of the system.

As far as our observations have gone, the conservation not only of energy but also of momentum and nuclear charge appears to hold in all nuclear reactions where the energy is liberated in the form of massive particles. In the cases, however, in which either positive or negative electrons are expelled in the transformation, there are certain difficulties in interpretation which have not yet been resolved.

The application of the law of conservation of energy to nuclear changes promises to give us very accurate and reliable data on the relative masses of the atomic nuclei—probably far more precise than we can hope to obtain by the mass-spectrograph, especially in the case of the heavier elements. The transformation data are in some cases inconsistent with the measurements of the masses by Aston and others, and a new scale of masses was recently suggested by Oliphant and Bethe which fit closely with observation. New measurements by Aston and others to fix the masses of the light elements with the greatest possible precision are now in progress, and it seems likely that the new values will be in much closer accord with those deduced from transformation data. It is noteworthy that practically every type of nuclear reaction takes place which is consistent with the laws of conservation, although the probability of the different reactions may vary widely. This is very well illustrated by the great variety of transformations that have been observed in the light elements like lithium, beryllium, or boron when bombarded by different types of particle.

Structure of Radioactive Nuclei.

The discovery of the neutron has much simplified our conception of the structure of nuclei, which are now believed to consist of neutrons and protons with probably helium nuclei as secondary units, composed of a very stable combination of two protons and two neutrons. These particles are contained in a minute nuclear volume with radius of the order 5×10^{-13} cm. which is surrounded by a high-potential barrier which prevents the escape of the particles. In the case of a heavy nucleus like that of uranium, where the potential barrier is very high, about 20 million volts, the α-particle has not sufficient energy to escape over the barrier. On wave-mechanical principles, however, there is a small but finite probability that the α-particle may escape through the barrier, carrying with it the energy which it possesses within the nucleus. Such a view gives a rational explanation of the spontaneous radioactivity shown by uranium and thorium and their products, and also accounts in a general way for the well-known Geiger–Nuttall empirical relation which shows a close connexion between the speed of the expelled α-particle from an element and the period of its transformation. In addition, Gamow has shown that on the wave-mechanics a charged particle like a proton has a small probability of entering a nucleus even if its energy is much too small on classical views to approach close to the nucleus. This theory accounts for the observation that comparatively slow particles can cause transformations, and also for the increase of efficiency of transformation with rise of energy of the bombarding particle.

It is difficult to obtain convincing evidence of the relation, if any, between the two units of structure of the atom, the neutron and the proton. It is difficult to measure the mass of the neutron with accuracy, but the evidence indicates that it is slightly heavier than the mass of the proton. It appears likely that the proton and neutron are closely related and under some conditions are mutually interchangeable within the nucleus.

The expulsion of a negative electron from the nucleus may be connected with the change of a neutron into a proton, while the escape of a positive electron is connected with the reverse operation. The peculiarities of the emission of electrons, both positive and negative, from radioactive atoms may possibly be traced to this interchange.

Before any detailed theory of nuclear structure can be attempted, it is necessary to find the nature and magnitude of the forces at small distances between the various components of the nuclear structure. Important information on these points ought to be obtained from a close study of the scattering of protons and neutrons in hydrogen. In default of any complete theory, some of the outstanding features of the relation between nuclei—for example, the differences between even- and odd-numbered elements—can be explained in a general way by assuming special types of forces between the elementary particles.

The spontaneous transformation of the radioactive bodies gave us the negative electron and α-particle as constituents of nuclei; the study of artificial transmutation has given us in addition three new particles, the proton, neutron, and positive electron, as well as a host of new radioactive bodies. In addition, as we have seen, we owe our conception of isotopes to the study of the chemistry of radioactive bodies, and our views of the nuclear structure of all atoms to observations on the scattering of α-particles.

It is clear that the study of radioactivity, both old and new, has been extraordinariln fruitful in extending our knowledge of the nature and varieties of atoms and of the way iy which one atom can be changed into another. Although much progress has been made in the last few years, much still remains to be done before we can hope to understand how the atoms have been built up from elementary particles or to grasp the significance of the relative abundance of the varieties of atoms in our earth.