Artificial Disintegration of the Elements.[1]

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SINCE the development of the atomic theory on an experimental foundation by Dalton, the progress of chemistry has been based on the central idea of the permanency and indivisibility of the atoms of the elements. The whole experience of chemistry for nearly a century had shown clearly that it was impossible to break up the atoms of the elements by the application of ordinary chemical and physical processes. This idea has had to be modified to some extent by the rapid growth of our knowledge during the last twenty years of the inner constitution of the atoms.

It is now generally accepted that the atoms of the different elements have all the same general type of structure. At the centre of the atom is a positively charged nucleus of minute dimensions which is responsible for most of the mass of the atom. This is surrounded by a distribution of electrons held in equilibrium by the forces from the nucleus. The electrons occupy rather than fill a region the diameter of which is of the order of 2×10^{-8} cm. The nuclear charge of the atoms follows a very simple rule first clearly brought to light by Moseley. The resultant nuclear charge of an atom is equal to its atomic or ordinal number, and varies from 1 " atom " of electricity in the case of hydrogen to 92 in the case of uranium. These ordinal numbers represent also the number of " planetary " electrons, as they have been called, which surround the nucleus of the atom. On this view of the atom, its ordinary physical and chemical properties, apart from its mass, are governed entirely by the nuclear charge, for this controls the number and arrangement of the external electrons on which these combining properties mainly depend. The mass of the atom is a property of the nucleus and exercises only a second order effect on the distribution of the electrons and so on the ordinary properties of the atom.

This point of view offers at once a simple explanation of isotopes, which consist of atoms of the same nuclear charge but of different nuclear masses. By the action of light and electrical discharges, we can readily remove one or more of the external planetary electrons from the atom, while by the action of X-rays and swift β-rays we may even eject one of the more strongly bound electrons of the system. In this way, we can effect, in a sense, a transformation of the atom, but it is merely a temporary one, and a new electron is soon captured from outside, and the atom is as before. The general evidence indicates that, even if a number of the planetary electrons were removed by suitable agencies, the stability of the nucleus would not be disturbed and the atom would in a short time regain its original structure. In order to effect a *permanent* change in the atom, it appears to be necessary to disrupt the nucleus itself. When once a charged unit of the nuclear structure is removed, the nuclear charge is altered permanently, and there is no evidence that this process is reversible under ordinary experimental conditions.

The discovery of the instability of the radioactive elements was the first severe shock to the idea of the permanency of all atoms. This radiating property is, however, confined mainly to the two heaviest elements, uranium and thorium, and their long series of descendants, and is shown only by two other elements, potassium and rubidium, and then only to a minor extent. Apart from these exceptions, the great majority of the atoms appear to be exceedingly stable structures, and to remain unaltered under ordinary conditions in this earth for periods of probably thousands of millions of years.

The property of radioactivity belongs to the nucleus, and is shown generally by the emission of a swift α-particle or helium nucleus and, occasionally, a swift electron or β-ray from the nucleus. The number and velocity of emission of these particles appear to be quite uninfluenced by the most powerful physical or chemical agencies, and to be an inherent property resulting from the instability of these very complex nuclei.

These results show clearly that the nuclei of heavy atoms contain both positively charged helium nuclei and negative electrons, and lead to the general view that the complex nuclei of all atoms are built up of hydrogen and helium nuclei and electrons. It is also generally supposed that a helium nucleus itself is a secondary unit composed of four hydrogen nuclei and two electrons. If this be the case, we may suppose the nuclei of all atoms to be composed ultimately of hydrogen nuclei, or " protons," as they have been termed, with the addition of negative electrons.

Radioactivity has thus not only provided us with the key of the structure of the elements, but has at the same time given us in the swift α- and β-particles a powerful method of probing the inner structure of the atom. By firing α-particles into the atoms of matter, we are able, by following the deflexions of the path of the α-particle, to find out the magnitude and law of the forces close to the nucleus and to form some idea of the dimensions of the latter. The general results suggest that the diameter of the nucleus of heavy atoms is of the order of 4×10^{-12} cm. or about 1/5000 of the diameter of the whole structure of the atom. The law of the inverse square of repulsion between electric charges is found to hold for a considerable region surrounding the nucleus. No doubt the size of the nuclei of light atoms is even smaller, and in the case of helium appears to be of the order of 5×10^{-13} cm. It is thus clear that the nuclei of atoms, although of very complex structure, are of exceedingly small dimensions.

It is probable that the forces which bind together the components of the nucleus are exceedingly powerful, and that consequently a large amount of energy will be required to disrupt its structure. The swift α-particle from radium or thorium, which is by far the most concentrated source of energy known to us, seems the agent most likely to succeed in an attack on the strongly-bound nucleus. The α-particle is expelled from radium with a velocity of about ten thousand miles per second, and thus has a speed twenty thousand

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times greater than that of a swift rifle bullet. Mass for mass, its energy of motion is four hundred million times greater than that of the bullet.

Whilst no doubt an α-particle fired directly at a heavy nucleus may penetrate its structure, its energy may at that stage be too small to cause a disruption. The attack on the lighter atoms is much more promising, for the repulsive forces are so much smaller that the α-particle may still retain much of its energy on entering the nuclear structure.

Before, however, considering experiments on this question, it is desirable to say a few words on the collision of α-particles with hydrogen nuclei, where no question arises of the disruption of the atom. When α-particles pass through hydrogen gas, there are occasional close collisions between the α-particles and the hydrogen nuclei, resulting in the appearance of high speed H-nuclei. These H-particles travel about four times the distance of the bombarding α-particle, and can be detected easily by the scintillations they produce on a zinc sulphide screen. From the ordinary principles of mechanics, the maximum speed given to an H-nucleus is 1·6 times that of the colliding α-particle, whilst the maximum energy communicated to it is 0·64 of the energy of the α-particle. It is found that the number of these swift H-atoms is far in excess of that to be expected if it be supposed that the α-particle and hydrogen nucleus behave as point charges for the very small distances involved in these violent collisions. In addition, the variation of the number with the velocity of the α-particle and the number shot off at different angles with the direction of the α-particle differ markedly from the results to be expected on the simple point theory.

It seems clear that not only has the α-particle a structure, but that the law of force at very short distances is entirely different from that of the inverse square. As a result of a careful investigation, Chadwick and Bieler concluded recently that the results of the collisions could be explained by supposing that the α-particle—to which the complexity is ascribed—behaves like a spheroid of axes 8×10^{-13} and 5×10^{-13} cm. Outside this surface, the law of the inverse square applies, but the forces increase so rapidly when the H-nucleus enters the spheroidal surface that it is rapidly turned back. This model of the helium nucleus is, no doubt, quite artificial, but it gives us some idea of its probable dimensions and the extent of the region in which new and powerful forces come into play.

We should consequently anticipate that, in a close collision of a swift α-particle with the nucleus of an atom more complex than that of hydrogen, the ordinary laws of force would break down when the distances separating the particle and nucleus became very small. It must be remembered that gigantic forces come into play in these nuclear collisions, and only very stable structures may be expected to survive the encounters.

The first observation which has to do with the main subject of my lecture was made some years ago. When the α-rays from a strong radioactive source pass through dry gases like oxygen or carbon dioxide, a small number of weak scintillations are observed on a screen beyond the range of the α-particles. These "natural" scintillations are believed to be due to atoms of hydrogen coming from the source, and probably result from a slight hydrogen contamination of the source during exposure to the radium emanation. If, however, dry air is substituted for oxygen or carbon dioxide, the number of scintillations is increased three or four times. This additional effect was found to be due to the presence of nitrogen, and was shown in a correspondingly greater degree by chemically prepared nitrogen. By suitable arrangements, it was found that the particles causing these scintillations were bent by a magnetic field to about the extent to be expected if they consisted of swift, charged H-atoms. It seemed probable from the beginning that these additional H-atoms, which appeared only in dry nitrogen and not in oxygen or carbon dioxide, must have their origin in a disintegration of the nitrogen nucleus by collision with a swift α-particle.

With the original counting arrangements, the scintillations were small in number, weak in intensity, and difficult to count with accuracy. Further progress has depended mainly on improvements in the counting microscope, with the object of increasing the intensity of the scintillations and the area of zinc sulphide screen under observation. By the use of wide-aperture objectives and special eyepiece lenses of low magnifying power, the counting of these scintillations has become much easier and more definite.

We shall now consider the methods adopted to investigate in more detail the effects observed in nitrogen and to test whether other elements behave in a similar way. The apparatus required is of the simplest character and consists merely of a brass tube, 3 cm. in diameter, provided with stopcocks by means of which dry gases may be circulated through it. At one end of the tube is a hole covered with a thin silver plate. The zinc sulphide screen is fixed 1·3 mm. away from the opening, leaving a slit in which absorbing screens of mica can be inserted. The radioactive source is fitted on the end of a rod so that its distances from the screen can be varied at will. In order to reduce the luminosity due to the β-rays from the source, the whole apparatus is placed in a strong magnetic field. It may be of interest to give a few details in illustration of the magnitude of the effects to be expected under different conditions. Suppose that the radioactive source, consisting of a brass disk coated on one side with an invisible layer of radium-*C* corresponding in γ-ray activity to 40 milligrams of radium, is placed 3·5 cm. from the screen and that a current of dry hydrogen is passed through the apparatus. Suppose the stopping power of the materials between the source and the zinc sulphide screen corresponds to 20 cm. of air, that is, it would suffice to stop an α-particle of range 20 cm. in air. The passage of the α-particles, which in this case have a range of 7 cm., through the hydrogen liberates a large number of high-speed H-atoms, which produce scintillations on the screen. Their number, seen through a special microscope which has a field of view of 40 sq. mm., is so great—thousands a minute—that it would be impossible to count them without reducing the activity of the source. As additional absorbing screens of mica are added, the numbers fall off rapidly, and for an absorption of, say, 30 cm. not a single H-scintillation can be observed per minute. A similar effect is shown if oxygen is substituted for hydrogen and a thin strip of paraffin wax or other hydrogen material is placed over the source. The number of H-scintillations observed for a given absorption depends only on the amount of hydrogen, and is quite independent of chemical combination. This is to be expected, for the forces required to set the H-nucleus in rapid motion are enormous compared with the weak forces involved in chemical combination. We thus conclude that, for α-particles of range 7 cm., no H-atoms from hydrogen in the free state or in chemical combination can be detected for an absorption greater than 30 cm. of air.

The oxygen which gives no scintillations is now replaced by dry air. At once we observe for an absorption of 30 cm. more than 100 scintillations per minute when for hydrogen we did not observe one. By adding mica screens we find that the scintillations cease for an absorption of 40 cm. It is clear that these particles, which come from nitrogen, have a greater range than free H-atoms bombarded by α-rays, so that the effect observed beyond 30 cm. cannot be ascribed to any hydrogen impurity in the nitrogen.

The air is now replaced by neutral oxygen, and thin foils of say copper, iron, silver, gold of stopping power corresponding to about 3 cm. of air are placed successively over the source. Not a single H-atom can be observed for an absorption of 30 cm. A piece of aluminium foil is substituted and at once the number of scintillations jumps to more than 100 per minute. Some of the scintillations are very bright, and we find that some of the particles are so swift that the absorption must be increased to 90 cm. before the scintillations vanish. It is clear that aluminium must give rise to a number of very long-range particles.

Thus if we examine the number of scintillations beyond the range of ordinary H-atoms, we are quite independent of any possible contamination of hydrogen in the material under examination. This is a great advantage, for we need not concern ourselves about the purity of the material as regards hydrogen. In this way, Dr. Chadwick and I have examined a large number of elements to test whether they emit particles of range more than 32 cm. When the element was not available, a compound of the element with an "inactive" element like oxygen was used. The material in the form of a fine powder is dusted on a thin gold foil, an adhesive film being used so that the average absorption of the material corresponded with 3-4 cm. of air, and was then exposed to the source of rays. With the exception of helium, neon and argon, all the elements up to atomic weight 40 have been tested. No element of atomic weight greater than phosphorus, 31, was found to give any effect, although it should be said that only a few of the elements of higher atomic weight have so far been examined.

A list of the elements examined in this way, from lithium to sulphur inclusive, is given in the following table. The second column gives the number of scintillations per minute per milligram activity of the source, namely, radium-*C*, for an absorption of 32 cm. of air. These numbers afford only a rough comparison of the effects given by different elements, for the conditions of the experiment, for example, the thickness and distribution of the film of material, varied from element to element. The fourth column gives the approximate range of the particles.

Element.	Material.	No. of particles per min. per mg. for the microscope used.	Maximum range of particles in cm. of air.
Lithium	Li_2O	—	—
Glucinum	GlO	—	—
Boron	B	0·15	*ca.* 45
Carbon	CO_2	—	—
Nitrogen	Air	0·7	40
Oxygen	O_2	—	—
Fluorine	CaF_2	0·4	over 40
Sodium	Na_2O	0·2	*ca.* 42
Magnesium	MgO	—	—
Aluminium	Al, Al_2O_3	1·1	90
Silicon	Si	—	—
Phosphorus	P (red)	0·7	*ca.* 65
Sulphur	S, SO_2	—	—

In addition to these, the following elements of higher atomic weight were examined: chlorine as $MgCl_2$; potassium as KCl; calcium as CaO; titanium as Ti_2O_3; manganese as MnO_2; iron, copper, tin, silver, and gold in the form of metal foils. In no case were any particles observed of range greater than 32 cm. of air. The question whether any of these elements give particles of range less than 32 cm. has not been examined.

It will be seen that the elements which give scintillations for an absorption of 32 cm. are boron, nitrogen, fluorine, sodium, aluminium, and phosphorus. The numbers for boron and sodium were distinctly less than for the other elements.

(*To be continued.*)

The Royal Academy.

THE representative of NATURE looking for points of scientific interest amongst the fourteen hundred or so annual exhibits at the Royal Academy may be excused if he sometimes feels depressed and is reminded of the proverbial searcher after a needle in a haystack, in so few of the pictures do objects having any direct connection with science appear. It has in past years been remarked that purely scientific work does not yet appeal to the Academy artist, and it is necessary to turn for points of interest to nature scenes such as may be found in pictures of sea, sky, snow, and country life.

In snow scenes J. Farquharson frequently has successful effects and "The Edge of the Forest" (239) this year is quite up to his standard. Another good snow effect, in this case associated with water, is contained in "A Yorkshire Bridge in Winter," by F. E. Horne (884). A successful landscape somewhat of the Leader type, the central feature of which is a group of pine trees, is shown by Frank Walton in 591. It is a pity that there is only this one example of his work in the exhibition. The title which A. J. Munnings has chosen for No. 111 does not lead one to expect a landscape, but the setting of the portraits which give