The Stability of Atoms

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The Stability of Atoms. *By* Sir Ernest Rutherford, *F.R.S.* (*Abridged report of a Lecture delivered before the Society on June* 10, 1921.)

During the latter half of the nineteenth century it was generally accepted that the atoms of the chemist and physicist were permanent and indestructible, and were uninfluenced by the most drastic physical and chemical agencies available. The existence of elements in the earth that appeared to have suffered no certain change within periods of time measured by the geological epochs gave a strong support to the prevailing view of the inherent stability of the elements. The discovery at the beginning of the twentieth century that the radio-active elements uranium and thorium were undergoing a veritable transformation, spontaneous and quite uncontrollable by the agencies at our disposal, was the first serious shock to our belief in the permanency of the elements. The essential phenomena which accompanied the series of transformations soon became clear. The disintegration of an atom was accompanied either by the emission of a swift atom of helium carrying a positive charge, or of a swift electron. With the exception possibly of potassium and rubidium, only the heavy radio-active elements showed this lack of stability. The great majority of the chemical elements appeared, as before, to be inherently stable and to be unaffected by the most intense forces at our disposal.

A number of attempts have been made from time to time to test whether the atoms of the elements can be broken up by artificial methods. Some thought that they had obtained evidence of the production of hydrogen and of helium in the electric discharge tube. It is, however, a matter of such great difficulty to prove the absence of these elements as a contamination in the materials used that the evidence of transformation has not carried conviction to the minds of the majority of scientific men.

In this lecture an account will be given of some preliminary experiments which indicate the possibility of artificial disintegration of some of the ordinary elements by a new method. Before discussing the results, it is desirable to say a few words on the modern conception of the structure of the atom. The results have been interpreted on the nuclear theory of atomic constitution. According to this view, the atom is to be regarded as consisting of a minute positively charged nucleus, in which most of the mass of the atom is concentrated, surrounded at a distance by a distribution of negative electrons which make the atom electrically neutral. We know that one or more of these outer electrons can be easily removed from the atom. The atom thus undergoes a kind of transformation, but only a temporary one, for the missing electrons are readily recaptured from neighbouring atoms. It seems not unlikely that the whole of the exterior electrons might be removed from an atom without interfering sensibly with the stability of its nucleus. Under suitable conditions, the atom would promptly regain its lost electrons and be indistinguishable from the original atom. In order to produce a *permanent* transformation of the atom, it is necessary to disintegrate the nucleus. Such a disruption of the nucleus occurs spontaneously in the radio-active atoms, and the processes appear to be irreversible under ordinary conditions.

The nucleus, however, is very small, and its constituent parts are probably held together by strong forces; and only a few agencies are available for an attack on its structure. The most concentrated source of energy at our command is a swift α-particle, and it is to be expected that an α-particle in its flight would occasionally approach so close to the nucleus as to disintegrate its structure. It is, indeed, from a study of the deflexion of swift α-particles in passing through matter that we have obtained the strongest evidence in support of the theory of the nuclear constitution of atoms. In the region surrounding a heavy nucleus, the inverse square law holds for the forces of repulsion between the charged α-particle and positively charged nucleus. The particle describes a hyperbolic orbit round the nucleus, and the amount of its deflexion depends on the closeness of its approach. It is from a study of this scattering of α-particles, combined with Moseley's interpretation of the X-ray spectra of the elements, that we know the magnitude of the resultant positive charge on the nucleus. This charge, in fundamental units, is equal to the atomic or ordinal number of the element, and varies between 1 for hydrogen and 92 for uranium. Recently Chadwick has shown by direct measurements of the scattering of α-particles that the charge on the nucleus is in close accord with Moseley's deduction, and has thus verified the correctness of this fundamental conclusion.

Some information about the dimensions of the nucleus can be obtained by studying the amount of scattering of α-particles at large angles by different atoms. The general results indicate that the nucleus of a heavy atom, if assumed spherical, cannot have a radius greater than 6×10^{-12} cm. It is not unlikely that the dimensions may be smaller than this. No doubt the size of a nucleus decreases with its atomic mass, and it is to be expected that the nucleus of the light elements should be smaller than for the heavy atoms. It is thus clear that the volume occupied by the nucleus is exceedingly small compared with that occupied by the atom as a whole.

A direct collision of an α-particle with this minute nucleus is thus a rare occurrence. It can be estimated that even in the case of heavy elements only one α-particle in about 10,000 makes a close collision with the nucleus. On account of the powerful repulsive field of the latter, the α-particle may either be turned back before reaching the nucleus, or be so diminished in energy that it is unable to effect its disruption. The case of the lighter elements, however, is much more favourable; for the repulsive forces are so much weaker that we may expect the α-particle to enter the nucleus structure without much loss of energy, and thus to be an effective agent in promoting the disintegration of the atom.

One of the most interesting cases to consider is that in which an α-particle (helium nucleus) collides with the nucleus of an hydrogen atom. Marsden showed that in some cases the *H*-atom is set in such swift motion that it can be detected by the scintillation produced on a zinc sulphide screen. The maximum speed obtainable is 1·6 times that of the incident α-particle, and such a swift *H*-atom is able to travel four times as far as the α-particle before being stopped. For example, the maximum range of a *H*-atom set in motion by an α-particle from radium *C*—range 7 cm. in air—corresponds to 29 cm. of air.

A close examination of the production of swift *H*-atoms by this method showed that the number was about 30 times greater than that to be expected if the colliding nuclei behaved as point charges repelling each other according to the inverse square law. This, and other observations, show that the law of the inverse square ceases to hold in such intense collisions, where the closest distance of approach is of the order 3×10^{-13}cm. It is probable that this distance is comparable with the actual dimensions of the structure of the α-particle itself. Some recent experiments by Chadwick and Bieler indicate that there is an abrupt change in the law of force at distances of about 5×10^{-13} cm. So far, no definite evidence has been obtained as to the nature of these forces which arise in the close collisions between nuclei. Attention should be directed to the enormous intensity of the electrical forces that come into play in such close collisions—forces much greater than can be brought to bear on an atom by ordinary laboratory methods. Unless the nucleus is a very stable structure, it is to be anticipated that it should be greatly disturbed, if not disintegrated, under the influence of such intense forces.

We must now consider the experiments which indicate that some of the lighter elements can be disintegrated by the action of α-particles. When a stream of α-particles is passed through dry air or nitrogen, a number of scintillations are observed far beyond the range of the α-particle. These scintillations are due to swift charged particles which are bent in a magnetic field like H-atoms set in swift motion by α-particles, and which, indeed, are undoubtedly H-atoms. Since this effect is not observed in dry oxygen or carbon dioxide, it appears likely that some of the nuclei of nitrogen have been disintegrated by the action of the α-particles. Recently these experiments have been repeated by Mr. Chadwick and myself under much better optical conditions for counting these comparatively weak scintillations. It has been found that, using radium C as a source of α-rays, the maximum range of the H-atoms from nitrogen atoms corresponds to 40 cm. of air, while the maximum range of the H-atoms from hydrogen, or any combination of hydrogen, is only 29 cm. under similar conditions. This result negatives the possibility that the presence of these H-atoms can be ascribed to any hydrogen contamination in the ordinary chemical sense.

This observation opened up a simple method of examining other elements besides nitrogen. Experiments were in all cases made beyond the maximum range (29 cm.) of ordinary H-atoms, so as to be quite independent of the presence of free or combined hydrogen in the material under examination. In this way it has been found that similar particles are produced in boron, fluorine, sodium, aluminium, and phosphorus. No definite effect has so far been observed for other elements of the production of particles with ranges greater than 29 cm. of air. The question of the production of slower velocity H-atoms has not so far been examined. The range of penetration of the atoms from aluminium is specially marked, being more than 80 cm. While no definite proof has yet been obtained of the nature of these ejected particles, it seems probable that they are in all cases H-atoms liberated from the nuclei of the elements in question. It is of special interest to note that H-atoms are only liberated in elements whose mass is given by $4n+2$ or $4n+3$ where n is a whole number. No H-atoms are observed from elements like carbon, oxygen, and sulphur, whose mass is given by $4n$. This is an indication that the α-particles are unable to liberate H-atoms from elements composed entirely of helium nuclei, but are able to do so from some elements composed of H-atoms as units as well as helium nuclei. It would appear as if the H-atoms were satellites of the main nuclear system and that one of them gained sufficient energy from a collision with an α-particle to escape from its orbit with a high speed. If the long-range particles from aluminium are H-atoms, it can be calculated that the maximum energy of motion is somewhat greater than that of the incident α-particle, indicating that the escaping fragment of the atom has gained energy from the system. It is of special interest to note that, in the case of aluminium, the direction of escape of the H-atom is to some extent independent of the direction of the α-particle. Nearly as many are shot in the backward as in the forward direction, but in the former case the average velocity is somewhat smaller. No element of mass greater than phosphorus (31) has been found to yield H-atoms. It would appear as if the constitution of the nucleus undergoes some marked change at this stage.

It should be remarked that the disintegration observed in these experiments is on a very minute scale. Only about one α-particle in a million is able to get close enough to a nucleus to effect its disintegration.

So far we have only been able to observe those fragments of atoms which escape with sufficient speed to travel further than the α-particles. Another very important method of examining the effects produced within the range of the α-particle has been recently examined by Mr. Shimizu. This depends on the discovery of Mr. C. T. R. Wilson that the tracks of ionising radiations can be made visible by sudden expansion of a moist gas, so that each ion becomes the centre of a visible globule of water. Wilson had previously observed an occasional sharp bend in the track of an α-particle, with a short spur attached, indicating the collision of an α-particle with an oxygen or nitrogen nucleus. By taking a large number of photographs of tracks of α-particles, Mr. Shimizu found a number of cases in which the track of the α-particle near the end of its range showed two nearly equal forks. It can readily be shown from the range and angle between the forks that these effects cannot be ascribed to a collision of the α-particle with a H-atom, or with a nucleus of oxygen or nitrogen. It would appear not unlikely that these forks indicate an actual disruption of the atom in which a helium nucleus is released. While this conclusion is only tentative, it will be of great interest to follow up further this new method of attack of a fundamental problem. It is remarkable that while only one α-particle in a million is able to liberate a H-atom from nitrogen, about one α-particle in 300 appears to show a forked track, indicating that this type of disintegration occurs much more frequently than the liberation of a H-atom.

If this interpretation proves to be correct, it shows that the amount of energy required to liberate a helium nucleus from a complex nucleus of a light atom is not great. Such a result is not inconsistent with modern ideas of the relation between mass and energy, for the fact that the atomic masses of carbon and oxygen are very nearly integral multiples of the mass of the helium atom is an indication that the helium nuclei are bound loosely together. On the other hand, if we suppose the helium nucleus itself to be composed of four hydrogen nuclei and two electrons, the loss of mass in the combination indicates that the helium nucleus is so stable a structure that it should not be dissociated by even the swiftest α-particle. This conclusion is supported by experimental observations as far as they have gone.