

The Structure of the Atom

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The present paper and the accompanying paper by Mr.C. Darwin deal with certain points in connexion with the “nucleus” theory of the atom which were purposely omitted in my first communication on that subject (Phil. Mag. May 1911). I brief account is given of the later investigations which have been made to test the theory and of the deductions which can be drawn from them. At the same time a brief statement is given of recent observations on the passage of α particles through hydrogen, which throw important light on the dimensions of the nucleus.

In my previous paper (loc. cit.) I pointed out the importance of the study of the passage of the high speed α and β particles through matter as a means of throwing light on the internal structure of the atom. attention was drawn to the remarkable fact, first observed by Geiger and Marsden¹ that a small fraction of the swift α particles from radioactive substances were able to be deflected through an angle of more than 90° as the results of an encounter with a single atom. It was shown that the type of atom devised by Lord Kelvin and worked out in great detail by J.J. Thomson was unable to produce such large deflexions unless the diameter of the positive sphere was exceedingly small. In order to account for this large angle scattering of α particles, I supposed that the atom consisted of a positively charged nucleus of small dimensions in which practically all the mass of the atom was concentrated. The nucleus was supposed to be surrounded by a distribution of electrons to make the atom electrically neutral, and extending to distance from the nucleus comparable with the ordinary accepted radius of the atom. Some of the swift α particles passed through the atoms in their part and entered the intense electric field in the neighbourhood of the nucleus and

¹Proc. Roy. Soc. A. LXXXII. p. 495 (1909).

were deflected from their rectilinear path. In order to suffer a deflexion of more than a few degrees, the α particle has to pass very close to the nucleus, and it was assumed that the field of force in this region was not appreciably affected by the external electronic distribution. Supposing that the forces between the nucleus and the α particle are repulsive and follow the law of inverse squares, the α particle described a hyperbolic orbit round the nucleus and its deflexion can be simply calculated.

It was deduced from this theory that the number of α particles falling normally on unit area of a surface and making an angle ϕ with the direction of the incident rays is proportional to

- (1) $\text{cosec}^4 \phi/2$ or $1/\phi^4$ if ϕ be small;
- (2) the number of atoms per unit volume of the scattering material;
- (3) thickness of scattering material t provided this is small;
- (4) square of the nucleus charge Ne ;
- (5) and is inversely proportional to $(mu^2)^2$, where m is the mass of the α particle and u its velocity.

From the data of scattering on α particles previously given by Geiger², it was deduced that the value of the nucleus charge was equal to about half the atomic weight multiplied by the electronic charge. Experiments were begun by Geiger and Marsden³ to test whether the laws of single scattering of α particles were in agreement with the theory. The general experimental method employed by them consisted in allowing a narrow pencil of α particles to fall normally on a thin film of matter, and observing by the scintillation method the number scattering through different angles. This was a very difficult and laborious piece of work involving the counting of many thousands of particles. They found that their results were in very close accord with the theory. When the thickness of the scattering film was very small, the amount of scattering was directly proportional to the thickness and varied inversely as the fourth power of the velocity of the incident α particles. A special study was made of the number of α particles scattered through angles varying between 5° and 150° . Although over this range the number decreased in the ratio 200.000 to 1, the relation between number and angle agreed with the theory within the limit of experimental errors. They found that the scattering of different atoms of matter was approximately

²Proc. Roy. Soc. A. LXXXIII. p. 492 (1910).

³Geiger and Marsden, Phil. Mag. XXV. p. 604 (1913).

proportional to the square of the atomic weight, showing that the charge on the nucleus was nearly proportional to the atomic weight. By determining the number of α particles scattered from thin films of gold, they concluded that the nucleus charge was equal to about the atomic weight multiplied by the electronic charge. On account of the difficulties of this experiment, the actual number could not be considered correct within more than 20 per cent.

The experimental results of Geiger and Marsden were thus in complete accord with the predictions of the theory, and indicated the essential correctness of this hypothesis of the structure of the atom.

In determining the magnitude of single scattering, I assumed in my previous paper, for simplicity of calculation, that the atom was at rest during an encounter with an α particle. In an accompanying paper, Mr. C. Darwin has worked out the relations to be expected when account is taken of the motion of the recoiling atom. He has shown that no sensible error has been introduced in this way even for atoms of such low atomic weight as carbon. Mr. Darwin has also worked out the scattering to be expected if the law of force is not that of the inverse square, and has shown that it is not in accord with experiment either with regard to the variation of scattering with angle or with the variation of scattering with velocity. The general evidence certainly indicates that the law of force between the α particle and the nucleus is that of the inverse square.

It is of interest to note that C.T.R. Wilson⁴ by photographing the trails of the α particle, later showed that the α particle occasionally suffers a sudden deflexion through a large angle. This affords convincing evidence of the correctness of the view that large deflexions do occasionally occur as a result of an encounter with a single atom.

On the theory outlined, the large deflexions of the α particle are supposed to be due to its passage close to the nucleus where the field is very intense and to be not appreciably affected by its passage through the external distribution of electrons. This assumption seems to be legitimate when we remember that the mass and energy of the α particle are very large compared with that of an electron even moving with a velocity comparable with that of light. Simple considerations show that the deflexions which an α particle would experience even in passing through the complex electronic distribution of a heavy atom like gold, must be small compared with the large deflexions actually observed. In fact, the passage of swift α particles through matter affords the most definite and straightforward method

⁴C.T.R. Wilson, Proc. Roy. Soc. A. LXXXVII. p. 277 (1912).

of throwing light on the gross structure of the atom, for the α particle is able to penetrate the atom without serious disturbance from the electronic distribution, and thus is only affected by the intense field associated with the nucleus of the atom.

This independence of the large angle scattering on the external distribution of electrons is only true for charged particles whose kinetic energy is very large. It is not to be expected that it will hold for particles moving at very much lower speeds and with much less energy – such, for example, as the ordinary cathode particles or the recoil atoms from active matter. In such cases it is probable that the external electronic distribution plays a far more prominent part in governing the scattering than in the case under consideration.

Scattering of β Particles

It is to be anticipated on the nucleus theory that swift β particles should suffer deflexions through large angles in their passage close to the nucleus. There seems to be no doubt that such large deflexions are actually produced, and I showed in my previous paper that the result of scattering of β particles found by Crowther⁵ could be generally explained on the nucleus theory of atomic structure. It should be borne in mind, however, that there are several important points of distinction between the effects to be expected for an α particle and a β particle. Since the force between the nucleus and β particle is attractive, the β particle increases rapidly in speed in approaching the nucleus. On the ordinary electrodynamics, this entails a loss of energy by radiation, and also an increase of the apparent mass of the electron. Darwin⁶ has worked out mathematically the result of these effects on the orbit of the electron, and has shown that, under certain conditions, the β particle does not escape from the atom but describes a spiral orbit ultimately falling into the nucleus. This result is of great interest, for it may offer an explanation of the disappearance of swift β particles in their passage through matter. In addition, it must be borne in mind that the swiftest β particle expelled from radium C possesses only about one-third of the energy of the corresponding α particle, while the average energy of the β particle is less than one-sixth of that of the α particle. It is thus to be

⁵Crowther, Proc. Roy. Soc. A. LXXXIV. p. 226 (1910).

⁶Darwin, Phil. Mag. XXV. p. 210 (1913).

anticipated that the large angle scattering of a β particle by the nucleus will take place in regions where the α particle will only suffer a small deflexion—regions for which the application of the simple theory may not have been accurately tested. For these reasons, it is of great importance to determine the laws of large angle scattering of β particles of different speeds in passing through matter, as it should throw light on a number of important points connected with atomic structure. Experiments are at present in progress in the laboratory to examine the scattering of such swift β particles in detail.

It is obvious that a β particle in passing close to an electron will occasionally suffer a large deflexion. The problem is mathematically similar to that for a close encounter of an α particle with a helium atom of the same mass, which is discussed by Mr. Darwin in the accompanying paper. Such large deflexions due to electronic encounter, however, should be relatively small in number compared with those due to the nucleus of a heavy atom.

Scattering in Hydrogen

Special interest attaches to the effects to be expected when α particles pass through light gases like hydrogen and helium. In a previous paper by Mr. Nuttall and the author⁷, it has been shown that the scattering of α particles in hydrogen and helium is in good agreement with the view that the hydrogen nucleus has one positive charge, while the α particle, or helium, has two. Mr. Darwin has worked out in detail the simple scattering to be anticipated when α particles pass through hydrogen and helium. It is only necessary here to refer to the fact that on the nucleus theory a small number of hydrogen atoms should acquire, as the result of close encounters with α particles, velocities about 1.6 times that of the velocity of the α particle itself. On account of the fact that the hydrogen atom carries one positive charge while the α particle carries two, it can be calculated that the some of the hydrogen atoms should have a range in hydrogen of nearly four times that of the α particle which sets them in motion.

Mr. Marsden has kindly made experiments for me to test whether the presence of such hydrogen atoms can be detected. A detail account of his experiments will appear later, but it suffices to mention here that undoubted evidence has been obtained by him that some of the hydrogen atoms are set in such swift motion that they are able to produce a visible scintillation on a zinc sulphide screen and are able to travel through hydrogen a distance

⁷Rutherford and Nuttall, Phil. Mag. XXVI. p. 702 (1913).

three or four times greater than the colliding α particle. The general method employed was to place a thin α -ray tube containing about 100 millicuries of purified emanation in a tube filled with hydrogen. The scintillations due to the α particle from the tube disappeared in air after traversing a distance of about 5 cm. When the air was displaced by hydrogen, the great majority of the scintillations disappeared at about 20 cm. from the source, which corresponds to the range of the α particle in hydrogen. A small number of scintillations, however, persisted in hydrogen up to a distance of about 90 cm. The scintillations were of less intensity than those due to the ordinary α particle. The number of scintillations observed is of the order of magnitude to be anticipated on the theory of single scattering, supposing that the nucleus in hydrogen and helium has such small dimensions, and that they behave like point charges for distance up to 10^{-13} cm.

There appears to be no doubt that the scintillations observed beyond 20 cm. are due to charged hydrogen atoms which are set in swift motion by a close encounter with an α particle. Experiments are at present in progress by Mr. Marsden to determine the number of hydrogen atoms set in motion, and the variation of the number with the scattering angle.

It does not seem possible to explain the appearance of such swift hydrogen atoms unless it be supposed that the forces of repulsion between the α particle and the hydrogen atom are exceedingly intense. Such intense forces can only arise if the positive nuclei have exceedingly small dimensions, so that a close approach between them is possible.

Dimensions and Constitution of the Nucleus

In my previous paper I showed that the nucleus must have exceedingly small dimensions, and calculated that in the case of gold its radius was not greater than 3×10^{-12} cm. In order to account for the velocity given to hydrogen atoms by the collision with α particles, it can be simply calculated (see Darwin) that the center of nuclei of helium and hydrogen must approach within a distance of 1.7×10^{-13} cm. of each other. Supposing for simplicity the nuclei to have dimensions and to be spherical in shape, it is clear that the sum of the radii of the hydrogen and helium nuclei is not greater than 1.7×10^{-13} cm. This is an exceedingly small quantity, even *smaller* than the ordinarily accepted value of the diameter of the electron, viz. 2×10^{-13} cm. It is obvious that the method we have considered gives a maximum estimate of the dimensions of the nuclei, and it is not improbable that the

hydrogen nucleus itself may have still smaller dimensions. This rises the question whether the hydrogen nucleus is so small that its mass may be accounted for in the same way as the mass of the negative electron.

It is well known from the experiments of Sir J.J. Thomson and others, that no positively charged carrier has been observed of mass less than of the hydrogen atom. The exceedingly small dimensions found for the hydrogen nucleus add weight to the suggestion that the hydrogen nucleus is the *positive electron*, and that its mass is entirely electromagnetic in origin. According to the electromagnetic theory, the electrical mass of a charged body, supposed spherical, is $\frac{2}{3} \frac{e^2}{a}$ where e is the charge and a the radius. The hydrogen nucleus consequently must have a radius about $1/1830$ of the electron if its mass is to be explained in this way. There is no experimental evidence at present contrary to such an assumption.

The helium nucleus has a mass nearly four times that of hydrogen. If one supposes that the positive electron, i.e. the hydrogen atom, is a unit of which all atoms are composed, it is to be anticipated that the helium atom contains, four positive electrons and two negative.

It is well known that a helium atom is expelled in many cases in the transformation of radioactive matter, but no evidence has so far been obtained of the expulsion of a hydrogen atom. In conjunction with Mr. Robinson, I have examined whether any other charged atoms are expelled from radioactive matter except helium atoms, and the recoil atoms which accompany the expulsion α particles. The examination showed that if such particles are expelled, their number is certainly less than 1 in 10,000 of the number of helium atoms. It thus follows that the helium nucleus is a very stable configuration which survives the intense disturbances resulting in its expulsion with high velocity from the radioactive atom, and is one of the units, of which possibly the great majority of the atoms are composed. The radioactive evidence indicates that the atomic weight of successive products decreases by four units consequent on the expulsion of an α particle, and it has often been pointed out that the atomic weight of many of the permanent atoms differ by about four units.

It will be seen later that the resultant positive charge on the nucleus determines the main physical and chemical properties of the atom. The mass of the atom is, however, dependent on the number and arrangement of the positive and negative electrons constituting the atom. Since the experimental evidence indicates that the nucleus has very small dimensions, the constituent positive and negative electrons must be very closely packed together. As Lorentz has pointed out, the electrical mass of a system of charged particles, if close together, will depend not only on the number of

these particles, but on the way their fields interact. For the dimensions of the positive and negative electrons considered, the packing must be very close in order to produce an appreciable alteration in the mass due to this cause. This may, for example, be the explanation of the fact that the helium atom has not quite four times the mass of the hydrogen atom. Until, however, the nucleus theory has been more definitely tested, it would appear premature to discuss the possible structure of the nucleus itself. The general theory would indicate that the nucleus of a heavy atom is an exceedingly complicated system, although its dimensions are very minute.

An important question arises whether the atomic nuclei, which all carry a positive charge, contain negative electrons. This question has been discussed by Bohr⁸, who concluded from the radioactive evidence that the high speed β particles have their origin in the nucleus. The general radioactive evidence certainly supports such a conclusion. It is well known that the radioactive transformations which are accompanied by the expulsion of high speed β particles are, like the α ray changes, unaffected by wide ranges of temperature or by physical and chemical conditions. On the nucleus theory, there can be no doubt that the α particle has its origin in the nucleus and gains a great part, if not all, of its energy of motion in escaping from the atom. It seems reasonable, therefore, to suppose that a β ray transformation also originates from the expulsion of a negative electron from the nucleus. It is well known that the energy expelled in the form of β and γ rays during the transformation of radium C⁹ is about one-quarter of the energy of the expelled α particle. It does not seem easy to explain this large emission of energy by supposing it to have its origin in the electronic distribution. It seems more likely that a very high speed electron is liberated from the nucleus, and in its escape from the atom sets the electronic distribution in violent vibration, giving rise to intense γ rays and also to secondary β particles. The general evidence certainly indicates that many of the high speed electrons from radioactive matter are liberated from the electronic distribution in consequence of the disturbance due to the primary electron escape from the nucleus.

Charge on the Nucleus

We have seen that from an examination of the scattering of α particles

⁸Bohr, Phil. Mag. XXVI. p. 476 (1913).

⁹See Rutherford and Robinson, Phil. Mag. XXV. p. 301 (1913).

by matter, it has been found that the positive charge on the nucleus is approximately equal to $\frac{1}{2}Ae$, when A is the atomic weight and e the unit charge. This is equivalent to the statement that the number of electrons in the external distribution is about half the atomic weight in terms of hydrogen. It is of interest to note that this is the value deduced by Barkla¹⁰ from entirely different evidence, viz. the scattering of X rays in their passage through matter. This is founded on the theory of scattering given by Sir J.J. Thomson, which supposes that each electron in an atom scatters as an independent unit. It seems improbable that the electrons within the nucleus would contribute to this scattering, for they are packed together with positive nuclei and must be held in equilibrium by forces of a different order of magnitude from those which bind the external electrons.

It is obvious from the consideration of the cases of hydrogen and helium, where hydrogen has one electron and helium two, that the number of electrons cannot be exactly half the atomic weight in all cases. This has led to an interesting suggestion by van Broek¹¹ that the number of units of charge on the nucleus, and consequently the number of external electrons, may be equal to the number of the elements when arranged in order of increasing atomic weight. On this view, the nucleus charges of hydrogen, helium, and carbon are 1, 2, 6 respectively, and so on for the other elements, provided there is no gap due to a missing element. This view has been taken by Bohr in his theory of the constitution of simple atoms and molecules.

Recently strong evidence of two distinct kinds has been brought in support of such a contention. Soddy¹² has pointed out that the recent generalisation of the relation between the chemical properties of the elements and the radiations can be interpreted by supposing that the atom loses two positive charges by the expulsion of an α particle, and one negative by the expulsion of a high speed electron. From a consideration of the series of products of the three main radioactive branches of uranium, thorium, and actinium, it follows that some of the radioactive elements may be arranged so that the nucleus charge decreases by one unit as we pass from one element to another. It would thus appear that van den Broek's suggestion probably holds for some if not all of the heavy radioactive elements. Recently Moseley¹³ has supplied very valuable evidence that this rule also holds for a number of the lighter elements. By examination of the wave-length of the characteristic X ray emitted by twelve elements varying in atomic weight

¹⁰Barkla, Phil. Mag. XXI. p. 648 (1911)

¹¹van der Broek, Phys. Zeit. XIV. p. 32 (1913).

¹²Soddy, Jahr. d. Rad. X. p. 188 (1913).

¹³Moseley, Phil. Mag. XXVI. p. 1024 (1913).

between calcium (40) and zinc (65.4), he has shown that the variation of wave-length can be simply explained by supposing that the charge on the nucleus increases from element to element by exactly one unit. This holds true for cobalt and nickel, although it has long been known that they occupy an anomalous relative position in the periodic classification of the elements according to atomic weights.

There appears to be no reason why this new and powerful method of analysis, depending on an examination of the frequency of the characteristic X ray spectra of the elements, should not be extended to a large number of elements, so that further definite data on the point may be expected in the near future.

It is clear on the nucleus theory that the physical and chemical properties of the ordinary elements are for the most part dependent entirely on the charge of the nucleus, for the latter determines the number and distribution of the external electrons on which the chemical and physical properties must mainly depend. As Bohr has pointed out, the properties of gravitation and radioactivity, which are entirely uninfluenced by chemical or physical agencies, must be ascribed mainly if not entirely to the nucleus, while the ordinary physical and chemical properties are determined by the number and distribution of the external electrons. On this view, the nucleus charge is a fundamental constant of the atom, while the atomic mass of an atom may be a complicated function of the arrangement of the units which make up the nucleus.

It should be borne in mind that there is no inherent impossibility on the nucleus theory that atoms may differ considerably in atomic weight and yet have the same nucleus charge. This is most simply illustrated by radioactive evidence. In the following table the atomic weight and nucleus charge are given for a few of the successive elements arising from the transformation of uranium. The actual nucleus charge of uranium is unknown, but for simplicity it is assumed to be 100.

Successive Elements	Ur ₁ →	Ur X ₁ →	Ur X ₂ →	U r ₂ →	Io →	Ra
Atomic weights	238.5	234.5	234.5	234.5	230.5	226.5
Charge on nucleus	100	98	99	100	98	96

Following the recent theories, it is supposed that the emission of an α particle lowers the nucleus charge by two units, while the emission of a β particle rises it by one unit. It is seen that Ur₁ and Ur₂ have the same

nucleus charge although they differ in atomic weight by four units.

If the nucleus is supposed to be composed of a mixture of hydrogen nuclei with one charge and of helium nuclei with two charges, it is *a priori* conceivable that a number of atoms may exist with the same nucleus charge but of different atomic masses. The radioactive evidence certainly supports such a view, but probably only a few of such possible atoms would be stable enough to survive for a measurable time.

Bohr¹⁴ has drawn attention to the difficulties of constructing atoms on the "nucleus" theory, and has shown that the stable positions of the external electrons cannot be deduced from the classical mechanics. By the introduction of a conception connected with Planck's quantum, he has shown that on certain assumptions it is possible to construct simple atoms and molecules out of positive and negative nuclei, e.g. by hydrogen atom and molecule and the helium atom, which behave in many respects like the actual atoms or molecules. While there may be much difference of opinion as to the validity and of the underlying physical meaning of the assumptions made by Bohr, there can be no doubt that the theories of Bohr are of great interest and importance to all physicists as the first definite attempt to construct simple atoms and molecules and to explain their spectra.

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¹⁴Bohr, Phil. Mag. XXVI. pp. 476, 857 (1913)