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ATOMIC NUCLEI[1]

I. INTRODUCTION

THE conception that atoms consisted of central positively charged nuclei of small dimensions surrounded by one or more systems of electrons whose aggregate charge of negative electricity exactly neutralized the nuclear positive charge, arose in an attempt by Rutherford[2] to explain the large angle scattering of α rays obtained when these traversed thin foils or sheets of various metals.

To account for the results obtained it was found necessary to assume that the positively charged nucleus contained nearly all the mass of an atom and that the dimensions of the nucleus were very small compared with the ordinarily accepted magnitude of the diameter of the atom.

On this view the electric field close to the nucleus was very intense and therefore sufficient to deflect α particles which in traversing sheets of metal happened to pass close to nuclei.

Assuming the electric field of nuclei to be central and to follow the inverse square law, Rutherford showed that an α particle projected so as to pass close to the nucleus of an atom would describe a hyperbolic orbit about the nucleus and that the magnitude of the deflection impressed upon it was determined by the closeness of its approach to the nucleus.

(*a*) The electric charge on nuclei.

On this theory Rutherford showed by deductions made from observations on the single encounter large angle scattering of α rays that the resultant charge on the nucleus was about ½ A e where A is the atomic weight of the

[1] Address of the vice-president and chairman of Section B—Physics, the American Association for the Advancement of Science, Toronto, December 29, 1921.

[2] Rutherford, *Phil. Mag.*, Vol. 21, p. 669, 1911; *Phil. Mag.*, Vol. 27, p. 448, 1914.

scattering element and e is the fundamental unit of electric charge. Elaborate experiments by Geiger and Marsden[3] on the scattering of α rays confirmed this view. The validity of the theory was also established in a convincing manner by C. G. Darwin[4] who made a thorough mathematical investigation of the deflexions which could ensue from an intimate encounter between an alpha particle in motion and a nucleus. In this investigation he showed that the results of the scattering experiments of Geiger and Marsden could not be reconciled with any law of central force except that of the inverse square.

In another entirely different field of investigation, namely, that of the scattering of X rays by light elements, Barkla[5] had shown in 1911 that the number of electrons in an atom which took part in the scattering of the X rays was equal to about one half of the atomic weight of the element.

Both lines of investigation therefore led to the view that the charge on the nucleus of an atom was given by ½ A e and that the number of electrons in an atom surrounding the nucleus was ½ A. It was the experiments on the scattering of α rays, however, which led to the view that the positively charged portions of atoms were nuclear in character with dimensions small compared with those of the atoms themselves, and that by far the greater part of the mass of the atoms was concentrated in the nucleus.

(*b*) Nuclear charge and atomic number.

In 1913 Van den Broeck[6] put forward the suggestion that the scattering of α particles was not inconsistent with the view that the charge on the nucleus of an atom was equal to Ne where N is the atomic number of the atom of the element concerned, *i. e.,* the number of the element when the elements are arranged in order of increasing atomic weight. A reference to a table of atomic weights will show that N is approximately equal to ½ A. The importance of this suggestion was soon made evident by the remarkable work of Moseley[7] on X ray spectra which followed in 1913 and in 1914. In this work Moseley showed that the frequencies of the vibrations of corresponding lines in the X ray spectra of the elements depended on the squares of numbers which varied by unity with the successive elements.

This relation, it was seen, could be readily explained by assuming that the nuclear charge of an atom varied by unity in passing from an atom of one element to that of another, and by assuming that the nuclear charge was given numerically by N, the atomic number.

The importance of Moseley's work was enhanced when it was seen that it gave us a new method of regarding the periodic classification of the elements based on the assumption that the atomic number or its equivalent, the nuclear charge, was of more fundamental importance than the atomic weight. As a result of Moseley's work it became possible not only to fix definitely the number of possible elements and the position of undetermined elements, but also to show that the properties of an atom were defined by a number which varied by unity in successive elements.

In Moseley's work the frequency of vibration of corresponding lines in the X ray spectra of the elements was not found to be exactly proportional to N^2 where N is the atomic number but to $(N - a)^2$ where a was a constant which had different values depending on whether the K or L series of characteristic rays was measured.

The investigations of Bohr[8] on the origin of radiations emitted by atoms are entirely in keeping with the assumptions that the nuclear charge is given by Ne, for he has shown that the frequency formula for X ray spectral lines must include a term $(N - a)^2$ with "a" having values approximately equal to those found by Moseley. In Bohr's investigation he showed that X rays originated in disturbances given to certain classes of extra nuclear electrons and that the quantity "a" represented a modifi-

[3] Geiger and Marsden, Roy. Soc. Proc. A., Vol. 82, p. 495, 1909.

[4] Darwin, *Phil. Mag.,* Vol. 27, p. 499, 1914.

[5] Barkla, *Phil. Mag.,* Vol. 21, p. 648, 1911.

[6] Van den Broeck, *Phys. Zeit.,* Vol. 14, p. 703, 1914.

[7] Moseley, *Phil. Mag.,* Vol. 26, p. 1024, 1913; *Phil. Mag.,* Vol. 27, p. 703, 1914.

[8] Bohr, *Phil. Mag.,* Vol. 26, p. 476, Sept., 1913.

cation of the electric field of the nucleus by the electric fields of the extra nuclear electrons within the atom.

II. On the Structure of Atoms

Through the advances made by a study of the scattering of α rays and of X rays the attack on the problem of the structure of atoms and the origin of radiations naturally proceeded upon two well-defined lines, namely:

1. The investigation of the constitution and properties of the nucleus, and

2. The investigation of the configuration and modes of vibration of extra nuclear electrons in atoms.

In pursuing this attack it has been assumed, with very good warrant, that the positive electric charges on nuclei are given by Ne where N is the atomic number of the element concerned, and that the number of extra nuclear electrons in an atom is N. For example, the number of extra nuclear electrons in various atoms is taken to be as follows: Hydrogen 1, helium 2, lithium 3, carbon 6, fluorine 9, neon 10, sodium 11, chlorine 17, argon 18, potassium 19, etc.

III. Positive Ray Analysis

This method of analysis was devised by Sir J. J. Thomson[9] and consisted in projecting successively through an electric and a magnetic field positively charged atoms or molecules, *i. e.,* those from which one or more extra nuclear electrons had been detached. By this means he was able to show that positive atom ions can be obtained with one, two, three, and, in the case of mercury, with eight positive elemental charges.

Among other results he has been able to show that such compounds as CH, CH_2 and CH_3 can exist with a recognisable though transitory existence. He has also shown that a substance having the molecular formula H_3 and bearing a single positive elemental charge can be obtained from various sources, a result which has been confirmed by Dempster, who showed that this molecular aggregate can be obtained with a transitory existence when an electric charge is passed through hydrogen. Perhaps the most notable discovery made by Thomson, however, was that neon existed in two forms with identical chemical properties, but with different integral atomic weights, namely, 20 and 22.

This discovery was of prime importance for it pointed to the probability of the general applicability of the principle which had been already found by Soddy and others to hold with the radioactive elements, namely, that the atoms of elements consist of *isotopes, i. e.,* that we have atoms of an element with identical chemical properties, but with different atomic masses. This discovery also offered an explanation of the non-integral values found by chemical analysis for the atomic weights of many of the elements. If it turned out, assuming the atomic weight of oxygen to be 16, that the atomic weights of the isotopes of an element were integers, then the non-integral value found by chemical analysis for the atomic weight of an element would result from the element existing as a mixture of its isotopes.

IV. Isotopes

Aston,[10] Dempster,[11] and later G. P. Thomson[12] have recently greatly improved Sir J. J. Thomson's methods of positive ray analysis with the result that they have been able to separate many of the elements of non-integral atomic weight such as chlorine, magnesium, argon and mercury into *isotopes,* each of which has an integral value for its mass. Chlorine, for example, has an atomic weight of 35.5 and can be separated by the positive ray method into an isotope of weight 35, and into one of weight 37. The validity of this result has been confirmed by Harkins,[13] who succeeded

[9] J. J. Thomson: Rays of positive electricity.

[10] Aston, *Phil. Mag.,* Vol. 38, p. 707, 1919; Vol. 39, p. 611, 1920; Vol. 40, p. 628, 1920; *Nature,* March 17, 1921; May 12, 1921.

[11] Dempster, *Phys. Rev.,* Vol XI, No. 4, p. 316, 1918; SCIENCE, Dec. 10, 1920; Apr. 15, 1921; Nov. 25, 1921.

[12] G. P. Thomson, *Phil. Mag.,* Aug., 1920, p. 240; *Phil. Mag.,* Nov. 1921, p. 858; *Nature,* Feb. 24, 1921.

[13] Harkins, SCIENCE, March 19, 1920.

in separating, by diffusion, a mass of chlorine into two portions with different densities. Mercury, too, has been found by positive ray analysis to consist of a number of isotopes, probably six, with integral atomic weights 197-200, 202, 204. As a confirmation of this result Bronsted and Hevesy[14] have shown that it is possible by fractional distillation to separate mercury into two parts with different densities.

The list of the elements in so far as they have been investigated for isotopes is given in Table I. In Table II following there is also assembled the isotopes of the various radioactive elements.

TABLE I
ISOTOPES

Element	At. No.	At. Wt.	Minimum No. of Isotopes	Masses of isotopes in order of their intensity
H	1	1.008	1	1.008
He	2	3.99	1	4.0
Li	3	6.94	2	7, 6
Be	4	9.1	1	9
B	5	10.9	2	11, 10
C	6	12.0	1	12
N	7	14.01	1	14
O	8	16	1	16
F	9	19	1	19
Ne	10	20.2	2	20, 22, 21?
Na	11	23	1	23
Mg	12	24.32	3	24, 25, 26
Si	14	28.3	2	28, 29, 30?
P	15	31.04	1	31
S	16	32.06	1	32
Cl	17	35.46	2	35, 37, 39?
A	18	39.88	2	40, 36
K	19	39.1	2	39, 41
Ca	20	40.09	1	40 (39, 40, 41)
Zn	30	65.4	4	64, 66, 68, 70
As	33	74.96	1	75
Br	35	79.92	2	79, 81
Kr	36	82.92	6	84, 86, 82, 83, 80, 78
Rb	37	85.45	2	85, 87
Sr	38	87.63	2	87, 85, 88?
I	53	126.92	1	127
Xe	54	130.32	5 (7?)	129, 132, 131, 134, 136, 128? 130?
Cs	55	132.81	1	133
Hg	80	200.6	6	197-200 202, 204

14 Bronsted and Hevesy, *Nature*, September 30, 1920.

V. DISCUSSION OF ISOTOPES

A glance at the results in Table I suggests a few observations.

(*a*) Isobares and radioactivity.

It is interesting to note that while iodine with an atomic weight 126.92 has but one isotope, 127, bromine with an atomic weight 79.92 has two, 79 and 81. Had it turned out that bromine consisted of but one isotope with weight 80 we should have had an example of an isobare, that is, an atom of one element with an atomic weight the same as that of an atom of a second element. It will be seen that one of the isotopes of krypton has an atomic weight 80.

It is also of interest to point out, as Harkins has done, that with magnesium having 3 isotopes and chlorine 2 it is possible to have nine isotopic forms of $MgCl_2$. As mercury has six isotopes there would follow the possibility of having 63 isotopic forms of Hg_2Cl_2. Similar considerations would apply in regard to other elements.

G. P. Thomson has recently found that strontium consists of two isotopes of weight 85 and 87. He failed however to find one of weight 88 or any higher number the necessity for which the atomic weight of strontium, 87.63, would seem to demand. As rubidium was shown to have isotopes of weight 87 and 85 we have in strontium and rubidium an example of isobaric isotopes, *i. e.*, the atoms of these two elements are identical in mass. As the nuclear charge of rubidium is 37e while that of strontium is 38e, it follows that the nuclei of rubidium atoms differ from those of strontium atoms only by the inclusion of one electron. This may possibly afford an explanation of the radioactivity which rubidium and its salts are known to exhibit. It has been shown that rubidium emits a soft radiation of beta particles, and since it is now generally agreed that radioactivity is a property of nuclei, it would follow that by the emission of beta rays, rubidium atomic nuclei are being transmuted into those of strontium. One should expect to find, then, strontium associated with the sources of rubidium.

TABLE II
ISOTOPES OF RADIOACTIVE SUBSTANCES

SUBSTANCE	AT. NO.	WEIGHT OF ISOTOPE					GROUP
Uranium	92	238 U_1	234 U_2				VI
Protoactinium	91	234 UX_2	230 Pa				V
Thorium	90	234 Th.	232 UX_1	230 I & UY	228 Ra.Th.	226 Ra.Act.	IV
Actinium	89	228 $Ms.Th_2$	226 Ac.				III
Radium	88	228 $Ms.Th_1$	226 Ra	224 ThX	222 Act.X		II
Emanation	86	222 Ra.Em.	220 Th.Em.	218 Act.Em.			VIII
Polonium	84	218 Ra.A.	216 Th.A.	214 Ra.C. Ac.A.	212 Th.C′	210 Ac.C′ Ra.F.	VI
Bismuth	83	214 Ra.C.	212 Th.C.	210 Ac.D. Ra.E.			V
Lead	82	214 Ra.B.	212 Th.B.	210 Ra.D. Act. B.	208 Th.D.	206 Ra.G. Ac.D.	IV
Thallium	81	210 Ra.C″	208 Th.C.″	206 AcC″			III

As potassium is also known to emit a radiation of beta particles we should expect the nuclei of atoms of potassium to be transmuted thereby into nuclei of calcium of the same weight, *i. e.,* we should expect to find that calcium consisted of two isotopes isobaric with those of potassium and therefore of weight 39 and 41. As regards this point the only evidence we have available is that furnished by the experiments of G. P. Thomson, who states that he found an isotope for calcium at 40 but with the magnetic field at his disposal it was impossible to separate lines even two units apart if such had existed for calcium. Thomson states, however, that it is certain that one or more isotopes of the weights, 39, 40, and 41 were present in his experiments. In some preliminary experiments made by Dempster an isotope of calcium was found at or near 40. He states, however, that the possibility of one of weight 39 is not excluded by his results. It will be interesting to see whether future experiments show that calcium has two isotopes of weight 39 and 41. Some additional evidence on this point might be gained by investigating the association of calcium with primary sources of potassium and its salts.

In this connection it is of interest to point out that lithium, sodium and cæsium have not been found to be radioactive. Moreover neither lithium and beryllium nor sodium and magnesium have any isotopes in common. Cæsium has been found to have but one isotope of weight 133 and although the isotopes of barium have not yet been investigated it would appear to be highly probable that, since the atomic weight of this element is 137.37, it will be found not to have any isotope isobaric with that of cæsium.

(*b*) Isotopes of cadmium.

Since the atomic weight of cadmium is 112.4 it will be seen that it will likely be found to have a number of isotopes, especially since zinc has been shown to have four and mercury six.

(*c*) Atomic weight and atomic number.

It will be noted that, with the possible exception of K^{39} and the doubtful Cl^{39} Table I does not show any other examples of *isobares.* There is a remarkable intermingling of the atomic weights and it is particularly noticeable in the case of ten consecutive integers representing the isotopes of bromine, krypton, and rubidium —Kr 78, Br 79, Kr 80, Br 81, Kr 82, Kr 84, Rb 85, Kr 86, Rb 87. This result makes it clear that the exact order of the chemically determined atomic weights is of little significance and that the anomalies such as argon and potassium and possibly too of tellurium and iodine as well as nickel and cobalt are merely due to the unequal relative proportions of their constituent isotopes.

From a consideration of the total abundance of various elements Harkins[15] pointed out that for the great majority of possible configurations it would probably be found that even atomic weight was associated with even atomic number and odd with odd. The results given in Table I, it will be seen, support this view. Of the halogens (odd atomic numbers) all six isotopes are odd. Of the alkali metals (odd atomic numbers) seven istopes are odd and only one even. On the other hand, of the isotopes of the inactive gases (even atomic numbers) fifteen are even and but three odd. This means that in the nuclei of most types of atom the number of electrons is an even number.

(*d*) The spectra of isotopes.

In an attempt made by Harkins, Aronberg and Gale[16] to see whether any method of distinguishing between the isotopes of an element could be obtained from a study of their spectra it was found that the wavelength of the line $\lambda = 4058$ A.U. as obtained from radiolead was 0.0044 A.U. greater than that from ordinary lead. A similar result was also obtained by Merton.[17] It has been pointed out however that this difference is about one hundred times greater than that predicted on the basis of Bohr's Theory of Radiation. Loomis[18] also has drawn attention to the unexpected satellites which Imes[19] found beside each line of the HCl absorption band at 1.76μ, and which measurements of his curves show to have an average wavelength of 16.4 A.U., longer than the lines which they accompany. These satellites Loomis has shown can be accounted for by assuming them to be due to the heavier of the isotopes of chlorine of weights 35 and 37. On this basis, his calculations show that the difference between the wavelength of the main line and its satellite should be 13 A.U., which it will be seen is in good agreement with observations of Imes.

(*e*) Structure of atomic nuclei.

By far the most important conclusion which can be drawn from the results recorded in Table I is that, with the exception of hydrogen, the weights of the isotopes of all the elements measured and, therefore almost certainly of all elements, are whole numbers, within the accuracy of the experiments—namely, about one part in a thousand. This result carries with it the possibility of greatly simplifying our ideas of mass. The original hypothesis of Prout, put forward in 1815, that all atoms were themselves built of atoms of protyle, a hypothetical element which he tried to identify with hydrogen, has been established on a new basis with the modification that the primordial atoms are of two kinds—atoms of positive and negative electricity. The unit of negative electricity, *the electron,* we have long been familiar with, but the unit of positive electricity, *which also appears to be the real unit of mass,* has remained unidentified experimentally until now as the positive nucleus of the atom of hydrogen. To this unit of mass and of positive electricity the name of "proton" has been given.

This profound modification of our views of the nature of mass has been very clearly set forth by Aston. The Rutherford atom whether in Bohr's or Langmuir's development of it consists essentially of a positively charged central nucleus around which are set planetary electrons at distances which are great compared with the dimensions of the nucleus itself. As has been stated the chemical properties of an element depend solely upon the atomic number which is the charge on its nucleus expressed in terms of the unit charge "e." A neutral atom of an element of atomic number N has a nucleus consisting of $K + N$ protons and K electrons and around this nucleus are set N electrons. The weight of an electron on the scale we are using is 0.0005 so that it may be neglected. The weight of the atom will therefore be $K + N$ so that if no restrictions are

15 Harkins, *Nature,* April 4, 1921.

16 Harkins, Aronberg and Gale, *Jl. of the Am. Chem. Soc.,* July, 1920, Vol. 42, p. 1328.

17 Merton, Proc. Roy. Soc., 96A, p. 388, 1920.

18 Loomis, *Nature,* Oct. 7, 1920.

19 Imes, *Astrophys. Jl.,* Nov., 1919.

placed on the value of K any number of isotopes is possible.

The first restriction is that excepting in the case of hydrogen K can never be less than N for the atomic weight of an element is always found to be equal to or greater than twice its atomic number.

The upper values of K also seem to be limited, for so far no two isotopes of the same element have been found differing by more than 10 per cent. of its mean atomic weight, the greatest difference is eight units in the case of krypton. The actual occurrence of isotopes does not seem to follow any law at present obvious, though their number is probably limited by some condition of stability.

Protons and electrons may therefore be regarded as the bricks out of which atoms have been constructed. An atom of atomic weight m is turned into one of atomic weight $m + 1$ by the addition of a proton plus an electron. If both enter the nucleus the new element will be an isotope of the old one, for the nuclear charge has not been altered. On the other hand, if the proton alone enters the nucleus and the electron remains outside, an element of next higher atomic number will be formed.

If both of these new configurations are possible they will represent elements of the same atomic weight but with different chemical properties. Such elements we have pointed out above are called isobares, and are already known to exist among the radioactive elements. (See Table II).

The element hydrogen, it will be noted, is unique in that its nucleus weight, 1.008, exhibits a departure from the rule of integers followed by the isotopes of all the other elements investigated. It will be noted, however, that it is the only atom in which the nucleus is not composed of protons and electrons closely packed together. It can be shown that with close packing of protons and electrons there must follow a reduction in effective mass, and that when four protons and two electrons are closely packed together as they must be in alpha particles, the nuclei of helium atoms, the resultant effective mass must be somewhat less than four times that of the hydrogen nucleus.

VI. THE DIMENSIONS OF ATOMIC NUCLEI, THEIR ELECTRIC CHARGES AND FIELDS OF FORCE

While phenomena connected with the scattering of α rays have led to such profound modifications in our views of atomic structure, it is of interest to note that through the agency of these same α rays we are likely to make still further advances in the problem of determining the ultimate structure of matter. Through the attacks now being rigorously pressed by Rutherford and his associates, the structure of the nuclei of atoms is slowly but steadily being revealed. Through the bombardment of atomic nuclei by α rays it has been found that the electric charges on atomic nuclei can be measured with a high degree of precision, estimates of the diameters of nuclei can be made, the field of electric force about a nucleus can be examined, and the structure of the nucleus itself can be broken down.

(*a*) Nuclear charges.

In his early experiments, Rutherford had shown from the experiments of Geiger and Marsden on the scattering of α rays that the charge on the nuclei of atoms of gold was within 20 per cent. equal to 100 e. More recently Chadwick[20] has shown by the use of direct and more refined methods that the charges on the nuclei of three types of atoms, namely, those of platinum, silver and copper, have the value of 77.4e, 46.3e and 39.3e respectively. As the atomic numbers of these elements are 78, 47 and 39, it will be seen that these results strongly confirm the view put forward by Rutherford as a result of the experiments of Moseley and others, which indicate that the nuclear charge is equal to Ne, N being the atomic number of the element.

(*b*) Nuclear dimensions and nuclear electric fields of force.

As mentioned above, Rutherford has shown by experiments on the scattering of α rays that the dimensions of atomic nuclei must be exceedingly small. For example, when high speed α particles collided with atoms of gold they were found to be turned back in their path at a distance of 3×10^{-13} cm. between

[20] Chadwick, *Phil. Mag.*, Dec., 1920, p. 734.

the centers of the α particles and those of the nuclei of the atoms of gold bombarded. This would go to show that in the case of the nucleus of an atom of gold, its radius is probably not greater than 3×10^{-13} cm. Further evidence in this direction has recently been adduced by Chadwick who found that the distance of approach of high speed α particles to the nuclei of platinum atoms was about 7×10^{-12} cm. and of low speed α particles about 14×10^{-12} cm.

In order to account for the velocity given to hydrogen atoms by collision with α particles, Rutherford calculated that the centers of the nuclei of helium and hydrogen must approach within a distance of 1.7×10^{-13} cms. of each other, assuming the law of repulsion to be that of the inverse square.

But the recoil phenomena of hydrogen atoms bombarded by α particles cannot be completely accounted for by assuming an inverse square law to hold for all distances between the centers of the α particle and the hydrogen nucleus. Rutherford suggested that roughly they could be explained by taking the α particle to be the equivalent of a plate of radius 3×10^{-12} cm. and assuming that as long as the α particle did not approach within this distance of the hydrogen nucleus, the ordinary inverse square law of repulsion held. If, however, the α particle did approach within this distance of the hydrogen nucleus a collision ensued which swept the latter straight forwards.

An attempt was made by Darwin[21] to work out the collision relations for all possible models of the α particle for which the electric fields would give integrable orbits. As a basis for this work he assumed the α particle to consist of 4 protons and 2 electrons, and found that a square nucleus in which the protons were arranged at the four corners of the square and the two electrons together at the center of the square, would give a field of force very similar to that of a bipole with collision relations roughly similar to those deduced from Rutherford's experiments.

[21] Darwin, *Phil. Mag.*, Vol. 41, p. 486, March, 1921.

This model has been put to the test by Chadwick and Bieler[22] and by McAuley[23] in a new series of investigations on collisions between particles and hydrogen nuclei and has been found to be not entirely satisfactory. In these experiments the earlier observations made by Rutherford were confirmed, namely, that α particles and hydrogen nuclei in collision do not behave as point charges. Not only is the angular distribution of the projected hydrogen nuclei different, but the numbers projected at small angles are for α particles of high velocity many times greater than those for point nuclei. For example, the observed number of hydrogen nuclei projected within 30° of the direction of incident α rays of range 8.2 cm. is more than 100 times as great as the theoretical number. The number projected within the same angle by α rays of range 4.3 cm. is 15 times the theoretical number. Also the observed variation of the numbers of projected hydrogen nuclei with velocity of the α particle is in the opposite direction from that given by the point theory. For example, α rays of range 8.2 cm. project within an angle of 30° nearly 3 times as many hydrogen nuclei as α rays of range 4.3 cm. On the basis of the point charge theory the α rays of 4.3 cm. range should give nearly 3 times as many as the 8.2 cm. α rays. It would appear, according to Chadwick and Bieler, that as a first approximation the α particle behaves in collision with a hydrogen nucleus as a body with properties intermediate between an elastic sphere and an elastic plate, and more like an elastic oblate spheroid of semi axes about 8×10^{-13} cm. and 4×10^{-13} cm., respectively, moving in the direction of its minor axis. On this view a hydrogen nucleus projected towards an α particle would move under the ordinary electrostatic forces governed by the inverse square law until it reached a spheroidal surface of the above dimensions. Here it would encounter an extremely powerful field of force and recoil as from a hard elastic body. The deductions made by Chadwick and Bieler are

[22] Chadwick and Bieler, *Phil. Mag.*, Vol. 42, p. 923, Dec., 1921.

[23] McAulay, *Phil. Mag.*, Vol. 42, p. 892, Dec., 1921.

interesting in that they emphasize the view that in dealing with collisions between α particles and hydrogen nuclei one must recognize that the inverse square law of repulsion ceases to hold in the immediate neighborhood of the electric charges carried by these nuclei. What the law of variation of the electric force is very close to an electric charge such as we have in an α particle can not as yet be deduced from the experimental evidence available. It is clear, however, that the electric forces in this region are of great intensity.

It is of interest to note that Chadwick and Bieler have pointed out that their experiments provide the only direct evidence we have as to the size of electrons. Assuming an α particle to consist of 4 protons and 2 nuclei it can be seen that the dimensions of the model of the α particle which their experiments have led them to put forward require that the radius of an electron cannot be greater than about 4×10^{-13} cm. Hitherto the only information we have had available as to the dimensions of the electron has been that obtained by calculations based on the assumption that its mass is wholly electromagnetic. Such calculations have given the value 2×10^{-13} cm. for its diameter. While it is clear that an inverse square law of force does not hold in the region extremely close to a nucleus, the experiments of Geiger and Marsden on the angular scattering of alpha particles by gold atoms between 5° and 150° show that it does hold very closely for distance, between 3.1×10^{-12} cm. and 36×10^{-12} cm. from the center of nuclei such as those of gold atoms. In this connection it will be recalled that the agreement between the experimental measurements of the X-ray K series spectra and the theoretical values of Debye[24] and Kroo[25] shows that the inverse square law still holds at the K ring of electrons. In the case of platinum the radius of the K-ring is about 10^{-10} cm. Thus measured from any point in the region between 3×10^{-12} cm. and 10^{-10} cm. from the nucleus of a heavy atom like gold or platinum, the nuclear charge is equal to the atomic number and the law of force is the inverse square. We may therefore conclude that no electrons are present in the region between the nucleus and the K ring.

This result is of special importance in connection with observations recently made by Barkla[26] and White and confirmed to a certain extent by Crowther,[27] which point to the possibility of stimulating atoms to emit radiations of wavelengths shorter than those of any of the known K-series. If these experiments should be corroborated by the results of later work it would appear that we must conclude that these J-rays and possibly, too, the more penetrating gamma rays originate within atomic nuclei and are not produced by disturbances of any of the systems of electrons situated within the atoms but outside their nuclei. In this connection it should be pointed out that Richtmyer[28] has failed to find any valid evidence of the existence of X-rays of the J type.

VII. THE STRUCTURE OF THE NUCLEUS

(*a*) H. particles.

The study of isotopes which we have briefly outlined above has led to very definite views regarding the structure of atomic nuclei. It is clear that all nuclei must be made up of protons and electrons held together by intense fields of force. Direct experimental evidence in support of this view has recently been brought forward by Rutherford[29] and those associated with him.[30] It is found that when swift alpha particles are made to pass through air or nitrogen a few particles having all the properties of protons are projected forward with velocities which give them a maximum range in air of 40 cm. No such long range particles are observed in oxygen or carbon dioxide. When swift alpha particles are made

[24] Debye, *Phys. Zeit.*, XVIII, p. 276, 1917.

[25] Kroo, *Phys. Zeit.*, XIX, p. 307, 1918.

[26] Barkla and White, *Phil. Mag.* (6), XXXIV, p. 270, 1917.

[27] Crowther, *Phil. Mag.*, (6), Vol. 42, p. 719, Nov., 1921.

[28] Richtmyer, *Phys. Rev.*, p. 433, March, 1921.

[29] Rutherford, Bakerian Lecture, Proc. Roy. Soc. (London), A., Vol. 97, p. 375, 1920.

[30] Rutherford and Chadwick, *Phil. Mag.*, S. 6, Vol. 42, p. 809, Nov., 1921.

to pass through hydrogen the maximum range obtainable for the recoil of hydrogen nuclei is never greater than the equivalent of 29 cm. in air. This makes it clear that the recoil of H particles or protons obtained with nitrogen can not arise from the presence of hydrogen as an impurity in the gas. The H particles must therefore originate in the nuclei of the nitrogen atoms which must therefore suffer disintegration under the intense bombardment of the alpha rays. Results similar to those obtained with nitrogen have been obtained with other elements that have been examined but it is of interest to note that it is only those elements whose atomic mass is given by $4n + 2$ or $4n + 3$ where n is a whole number that give rise to H particles. Elements of mass 4n like carbon, oxygen and sulphur show no effect. In Table III the results obtained so far are summarized.

TABLE III

Recoil H Particles and Their Ranges

Element	Mass	$4n + 2$ or $4n + 3$	Maximum range in cm. of air of H particles or protons expelled under alpha ray bombardment
Boron	11	$2 \times 4 + 3$	Ca 45
Nitrogen	14	$3 \times 4 + 3$	40
Fluorine	19	$4 \times 4 + 3$	40
Sodium	23	$5 \times 4 + 3$	42
Aluminium	27	$6 \times 4 + 3$	90
Phosphorus	31	$7 \times 4 + 3$	65

(*b*) Ranges of H particles.

With aluminium it will be seen the range of the expelled protons is more than twice as great as for those liberated from nitrogen.

The number of H particles expelled from the nuclei of the atoms of different elements is found to vary greatly with the speed of the impinging alpha rays. When alpha particles from thorium C which have a range of 8.2 cm. in air are used the H particles are relatively numerous. With α particles having a 7 cm. range in air, *i. e.,* those emitted by Ra.C, the number of H particles ejected is considerably smaller. With alpha rays of range 5 cm. in air the number is exceedingly small. With aluminium no H particles appear to be released by alpha particles of range less than 5 cm.

(*c*) H particle satellites: backward recoil.

In experiments with aluminium foils bombarded by alpha rays it was found that the direction of escape of the H particles was to a large extent independent of the direction of the impinging alpha particles. Nearly as many were expelled in the backward as in the forward direction. The maximum range for H particles ejected in the backward direction was, however, found to be less than that of H particles projected forwards. In the case of the former the maximum range was 67 cm. while with the latter it was 90 cm. air equivalent.

In order to explain the ejection of H particles in all directions Rutherford and Chadwick have put forward a simple explanation. They suppose that in such an atom as that of nitrogen the main nucleus has a mass 12 and that it has two H particles moving in an orbit round and close to it. The manner in which the collisions are supposed to occur is shown in Fig. I.

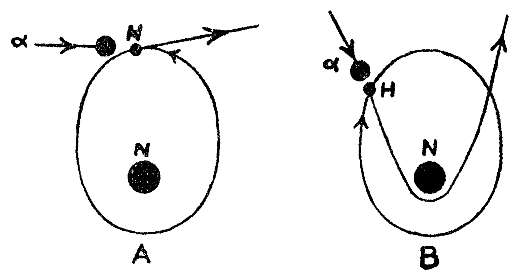


Fig. 1

If the collision occurs as in A the H particle is driven in the forward direction of the alpha particle and away from the nucleus; if, as in B, the H particle is driven towards the nucleus; it describes an orbit close to the latter and escapes in a backward direction. The difference in the velocity of the H particles in the forward and backward directions is probably due to the fact that the main nucleus has been set in motion, in the direction of the alpha particle, before the close collision with the H particle occurs. On this view the relative velocity of the H particle and the residual nucleus is the same whether the H particle escapes in the backward or forward direction, but the actual velocity in the backward direction is less.

(*d*) Attraction between positive charges.

This explanation, it will be noted, implicitly assumes that positively charged bodies attract one another at the very small distances involved in the close collisions between alpha particles and atomic nuclei. Rutherford and Chadwick have pointed out that in order that the colliding alpha particle may communicate much of its momentum to an H particle satellite the latter must be held by strong forces to the nucleus. If, however, the H satellite is very close to the nucleus the alpha particle may have to communicate a considerable fraction of its momentum to the central nucleus, and the velocity of escape of the H satellite is correspondingly reduced. This for example may be the explanation why the alpha particles from aluminium are ejected at higher speeds than those from phosphorus of higher nuclear charge. In phosphorus the H satellites may move so close to the nucleus that the alpha particle is able to give a smaller share of its momentum to the H satellite than in the case of the more distant satellite of aluminium.

(*e*) Close satellites.

So far no H particles have been obtained with elements heavier than phosphorus. The failure to obtain them with such elements may be due to the fact that the H atoms either move very close to the central nucleus or are incorporated in it.

(*f*) Disruption potential.

The theory of nuclear disintegration put forward would seem to demand a definite disruption potential for nuclei having one or more H satellites revolving about them. The experiments with aluminium support this view as no H particles are released from aluminium nuclei by α particles of range in air less than 5 cm. The disruption potential for the nuclei of aluminium atoms, *i. e.,* the potential difference required to communicate the same energy to an electron as is possessed by the α particle is of the order of six million volts. The corresponding potential to liberate an electron from the K or inner ring of electrons of the atoms of aluminium is only about 2,200 volts.

By a simple calculation it can be shown that the results obtained by Rutherford indicate that by operating at six million volts one could with the daily expenditure of 600,000 H.P. disintegrate the nuclei of three cubic feet of nitrogen and obtain thereby not only the recovery of the 600,000 H.P. but also approximately 80,000 H.P. in addition.

(*g*) Atomic weight of nitrogen.

If the view put forward is correct that the H particles are satellites of the central or main nucleus the mass of the H satellite,—since it is not in the "closely packed" condition,—should not be very different from that of a free H nucleus. Assuming that the nitrogen nucleus is derived from that of carbon by the addition of two H satellites and one electron, one might expect the atomic weight of nitrogen to be 14.016, assuming $C = 12.00$, and $H = 1.008$ in terms of $O = 16$. By a slight refinement of Aston's positive ray analysis it should be possible to examine this point.

(*h*) Atomic energy.

A matter of primary importance which has emerged from the experiments on the disintegration of atomic nuclei is that the energy of the H particle as it is ejected from aluminium atoms by the impact of α particles is 1.40 times the energy of the impinging α particles. Even when ejected in a backward direction the released H particle has kinetic energy about 13 per cent. greater than that of the α particle, causing its ejection. This additional energy must come from the atom in consequence of its disintegration. We have therefore in these experiments of Rutherford strong indications of a method of attack which, if followed up, may open a way to the release of the stores of atomic energy existing in ordinary materials about us.

(1) H_3 particles.

In addition to the long range H particles liberated from nitrogen, the passage of α particles through oxygen as well as through nitrogen gives rise to much more numerous swift atoms which have a range in air of about 9 cms compared with that of 7.0 cm. for the colliding α particles. From preliminary observations on these particles they appear to have a mass of 3 and to carry a positive charge 2e. They would thus seem to be the nuclei of an isotope of helium. A number of experiments have been made by Rutherford with α particles traversing gases other than oxygen and nitrogen with the object of definitely establishing the origin of these particles. The imperfection of metal foils, used in the experiments, from the point of view of α rays is very great and as yet no very final conclusions can be drawn from the observations. So far, there is always the possibility that these particles may come from the source of α rays. The H_3 particles obtained from nitrogen are from five to ten times as numerous as the H particles so that if these particles really originate in the nuclei of nitrogen atoms, it is clear that the nitrogen nuclei can be disintegrated in two ways and that the two forms of disintegration must be independent and not simultaneous. Since the H_3 and α particles both carry the positive charge 2e, and the range of the former is 27 per cent. greater than that of the latter, it can easily be shown that the H_3 particles have a velocity 20 per cent. greater than that of the α particles. The kinetic energy of the H_3 particles must therefore be about 8 per cent. greater than that of the 7 cm. range α particles. If, therefore, the H_3 particles are ejected from nitrogen nuclei by the α particles there must be a gain of 8 per cent. in energy of motion even though we disregard the subsequent motion of the disintegrated nucleus and of the colliding α particle. It will be interesting to follow developments in connection with these H_3 particles. If their existence be confirmed by future experiments and it can be shown definitely that they originate in the nuclei of atoms of such elements as oxygen and nitrogen, then we shall have in their production a second example of the release of atomic energy through the agency of α rays.

(*j*) Alpha particles.

Attention should be drawn to the branched X-ray cloud tracks recently obtained by Takeo Shimizu[31] by the use of C. T. R. Wilson's beautiful method of making visible the tracks of ionising rays in gases. According to Rutherford if about one hundred thousand α rays from Radium C pass through air, on an average there will be one close nuclear collision which results in the ejection of a swiftly moving H particle. In Shimizu's experiments he found that about one in every three hundred α rays traversing air produce a branched track. These branched tracks cannot therefore have been produced by the ejection of an H particle. One striking feature of the Shimizu branched tracks is that their shapes and sizes are very similar and the lengths of the two limbs of the branches are approximately the same. The angle between the two branches seems to vary but little and judging from the photographs, an example of which taken from Shimizu's paper is shown in Fig. 2, it appears to be about equal to a right angle. With these branched tracks the branching always takes place near the end of the path of the α particle.

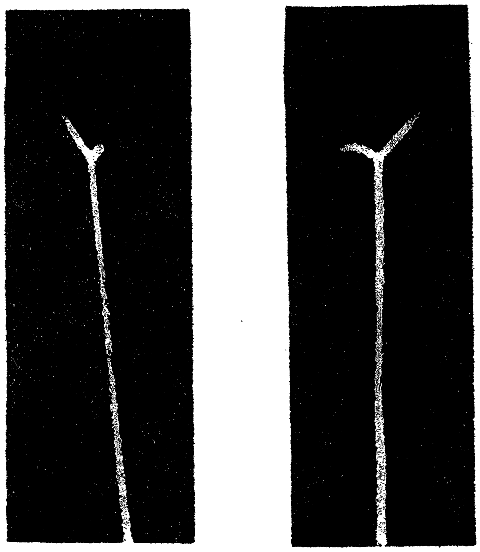


FIG. 2

Photograph of a branched α-ray track viewed from two positions at right angles to each other. Actual magnification 5.5.

In this regard they differ from the short-spurred tracks obtained by C. T. R. Wilson[32] where the abrupt bending of the α ray track took place at different distances from the source of the α particles. In Wilson's experiments the angle between the direction of the short spur and that of the deflected α particle

[31] Shimizu, Proc. Roy. Soc., Series A, Vol. 99, pp. 425 and 432, Aug., 1921.

[32] C. T. R. Wilson, Proc. Roy. Soc., A, Vol. 87, 1912.

was about 107°. This fact, together with the observed relative length of the spur and the track of the deflected α particle seems to show that the spur was due to an oxygen atom recoiling under close impact with the alpha particle. The Shimizu branched tracks, however, appear to be similar to what one would expect to get, on the basis of Darwin's calculations, in a closed collision between an α particle and the nucleus of a helium atom.

This idea naturally suggests that we have in the Shimizu branched tracks examples of the disruption of nuclei with the liberation of He_4^{++} or alpha particles. If this conjecture should turn out to be correct it would indicate that α particles can exist as definite units within the nuclei of atoms of one or more of the gases which make up air. It would be of interest to see if the Shimizu tracks can be obtained in pure nitrogen and also in pure oxygen and other simple gases. Since α particles are known to exist at definite units within the nuclei of the atoms of the radioactive elements, it would not be surprising to find their occurrence in the nucleus of an element such as oxygen. It would be of special interest, however, to find out the lightest atom other than that of helium in the nucleus of which the α particle exists as a unit.

(*k*) Models of atomic nuclei.

It is difficult with the present state of our knowledge to go into details regarding the possible structure of the nuclei of even the lighter and presumably less complex atoms. It would seem, however, that there is strong evidence for the view that among the possible units or structural bricks out of which nuclei are constructed are protons (H_1^{+}) and α particles (He_4^{++}). There is also some evidence that the particle (He_3^{++}), *i. e.,* the nucleus of a triprotonic isotope of helium can exist as a distinct elementary unit in the nuclei of some types of atom. With such or somewhat similar combining units, attempts have been made by Harkins[33] to work out a constitutional formula applicable to the nuclei of all the elements. The validity of such generalizations can be firmly established only through elaborate and varied experiments, but in the meantime they can at least serve as guides in arranging schemes of attack for prospective experimental work.

A rather suggestive set of models of the atomic nuclei of helium, carbon, nitrogen, and oxygen, based on the ideas of Rutherford is shown in Figs. 3, 4, 5, and 6. In these, the particles H_1^{+}, He_3^{++} and He_4^{++} are utilized as constituent units. Similar models can be easily made for the nuclei of the atoms of other elements. From these models one would expect to find He_3^{++} particles released by the disruption of carbon atoms, He_3^{++} and H_1^{+} particles when nitrogen atoms are broken up and He_4^{++} as well as He_3^{++} particles when oxygen nuclei are disintegrated. It will be seen that the models provide the requisite masses and resultant electric charges for the nuclei they represent. In so far as the nuclei of helium, nitrogen and oxygen atoms are concerned the constitution presented would seem

[33] Harkins, *Phys. Rev.*, Vol. 15, p. 73, 1920.

FIG. 3
HELIUM NUCLEUS

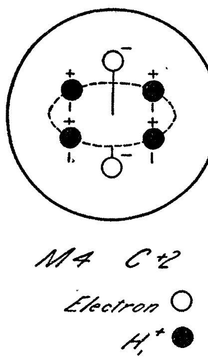


FIG. 4
CARBON NUCLEUS

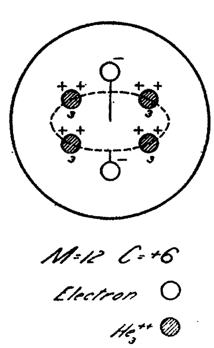


FIG. 5
NITROGEN NUCLEUS

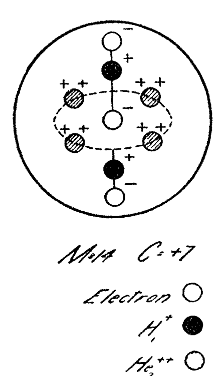
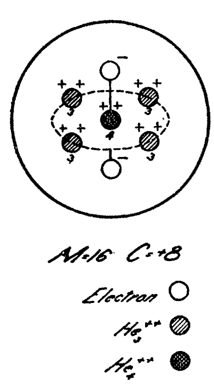


FIG. 6
OXYGEN NUCLEUS



to be not incompatible, at least with the results of many of the experiments of Rutherford and of those who are so brilliantly cooperating with him to reveal to us the ultimate structure of matter.

J. C. McLennan

The Physical Laboratory,
University of Toronto,
December 29, 1921

PROGRESS IN METRIC STANDARDIZATION

Mark Twain remarked that people talked a great deal about the weather and yet he never heard of anybody doing anything about it. The same observation might also be made in reference to the metric system. As scientists we believe in it and through our organizations such as the American Association for the Advancement of Science, the American Chemical Society, etc., we pass resolutions in favor of its adoption, but we do little towards making its use more general. We use the metric system in certain parts of our work but we continue to purchase our chemicals and supplies on the basis of the so-called English "system." The American Chemical Society has resolved to "do something about it" and the first step is to purchase our chemicals and supplies on a metric basis and thus "clean our own house."

The manufacturers and dealers are entirely willing to cooperate, but they feel that it is absolutely necessary for the consumers to take the initiative. A list of some 40 manufacturers and dealers, who are ready to quote in metric units, has been compiled by the Metric System Committee. *Cf. J. Ind. and Eng. Chem.* 13, 1068 *Nov.* 1921. Several firms already use metric packages and some of them exclusively such as the Eastman Kodak Company, Powers-Weightman-Rosengarten Co., etc.

Users of chemicals are now asked to write their specifications in metric units in order to aid in this movement. Over 300 colleges and universities have already agreed to cooperate in the movement, with only one institution known to be opposed to the change. Over 250 technical firms have agreed to purchase their pure chemicals and chemical supplies in metric packages. Firms have been urged to write to the Committee "even if opposed to the movement." It is significant that less than 3 per cent. of those heard from are opposed, which prompts us to believe that in a short time pure chemicals in America may be packed exclusively in the standard metric packages as recommended by the Committee on Guaranteed Reagents and Standard Apparatus (*cf. J. Ind. Eng. Chem.* May 1921), Dr. W. D. Collins, Chairman.

We now ask that all scientists—physicists, biologists as well as chemists—make a point of ordering chemicals in metric units. It is not practicable to reach by letter all of the teachers of science in our schools and colleges as well as those using chemicals in the industries, hence we are making this general appeal so that the transition period may be made as short as practicable. We have had printed "stickers" stating that "orders must be filled and billed in metric units" which will be sent to any correspondent for the asking.

No scientist would willingly join a movement which would work an injury to American industry. We have considered the question whether the compulsory adoption of the metric system would be injurious to industry and we believe that it would be of distinct benefit not only in world trade but in our intercourse here at home. The DeLaval Separator Company has already changed over to the metric basis in a purely mechanical enterprise and they find that the cost of the change does not even "show up" in the manufacturing costs.

In education the saving by abolishing our out-of-date system would be enormous, estimated by Dr. Wolf to be an aggregate of a million years in a single generation. The promotion of understandings with other nations tends to the promotion of world peace and the cost of not adopting the system used by practically every nation in the world except the English and ourselves may far exceed in a single generation the cost of making the change.

We need local committees to get the metric system properly taught in the schools. Doctors are writing prescriptions in metric units