Electricity and Matter.[1]

By Sir ERNEST RUTHERFORD, F.R.S.

IT has been customary in the earlier Kelvin lectures to give an account of some phase of Kelvin's work. I could easily follow this custom by concentrating on the publications of Kelvin that deal with the proof of the atomic nature of matter and the dimensions of atoms and molecules, including the first suggestions of the mechanism of atomic constitution. This was a subject in which Kelvin was permanently interested. In his Royal Institution lecture of 1883, reprinted in "Popular Lectures and Addresses," vol. 1, he gives an illuminating account of the different lines of evidence that all converge to a cumulative proof that matter is coarse-grained or atomic in structure and set a definite minimum limit to the dimensions of the atom. His deduction of the diameter of the water molecule from the cooling effect observed when a water film is stretched, is one of the most notable of these examples. In his later papers he accepts Stoney's arguments in support of the atomic nature of electricity, and in a paper of curious title, "Æpinus Atomised,"[2] he restates the old theory of Æpinus of the nature and relation of positive and negative electricity in a more modern form, by assuming that the negative electricity in an atom is distributed in the form of definite units called "electrions"—or electrons, as we should now term them—held in equilibrium embedded in a sphere of uniform positive electrification. This was the first type of model atom put forward. A similar type of atom, developed and worked out in detail by Sir J. J. Thomson, played a notable part in giving a concrete view of atomic structure which was directly amenable to mathematical calculation. In some of his later papers, Kelvin devised types of atoms which, under certain disturbances, broke up with explosive violence, simulating in behaviour the atoms of radium. While keenly interested in such speculations, there remained the curious anomaly that he did not accept entirely the current explanation that radio-activity was a consequence of the successive disintegrations of atoms.

The discovery in 1897 of the individual existence of the negative electron of small mass, and the proof that it was a component of all the atoms of matter, was an event of extraordinary significance to science, not only for the light which it threw on the nature of electricity, but also for the promise it gave of methods of direct attack on the problem of the structure of the atom. This discovery of the electron, coupled with the recognition of the atomic nature of electricity, has created a veritable revolution in our ideas of atoms.

The first definite proof of the close relations that exist between electricity and matter we owe to the famous experiments of Faraday on the passage of electricity through electrolytes. It was clear that the simple numerical relations found by him between the electrochemical equivalents of the elements and their atomic weights could be simply interpreted by assuming that electricity was atomic in character and that the charges carried by the individual ions were integral multiples of a fundamental unit of charge. It is curious to note the long interval that elapsed before the idea of the atomic nature of electricity was generally accepted by men of science—possibly because of the great difficulty of obtaining confirmatory evidence. The suggestion was mentioned by Maxwell and Helmholtz, although with reservation, but was revived with conviction by Johnstone Stoney, who suggested that the name "electron" should be applied to the fundamental unit of electricity and made a rough estimate of its magnitude. Actually, as we know, the term "electron" is now used to denote not the actual value of the unit of charge, but the free atom of negative electricity.

Following the discovery of the independent existence of the electron and the proof of the production of charged ions in gases by X-rays and other radiations, it was implicitly assumed by men of science that electricity must be atomic in nature, and all the experimental data were interpreted on this view. It was found by Townsend that the charge carried by the ions produced in gases and by the electron itself was numerically equal to that carried by the hydrogen ion in the electrolysis of water, which was taken as the fundamental unit. By the ingenious device of balancing the weight of a charged drop by the attraction of the electric field, Millikan was able to give a very direct and convincing proof of the correctness of this view and to determine the magnitude of the fundamental unit with great precision. Knowing the value of this constant, the electrochemical data give us immediately the mass of the atom of each of the elements. While no one now doubts the atomic nature both of matter and of electricity, it should be noted that the atomic nature of matter is in reality a consequence of the discrete nature of electricity, for all the evidence indicates that the atom itself is a purely electrical structure.

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It was soon recognised that the negative electron of small mass was an actual disembodied atom of electricity, and that its apparent mass was electrical in origin. Sir J. J. Thomson had shown as early as 1881 that a charged body in motion behaved as if it had an additional electric mass due to its motion. The moving charge generates a magnetic field in the space surrounding it, resulting in an increase of energy of the moving system which is equivalent to the effect produced by an increase of the mass of the body. The experiments of Kaufmann and others on the swift electrons ejected from radium showed that the mass of the electron, while sensibly constant for slow fields, increased rapidly as the velocity of the electron approached that of light. This variation of mass was in good agreement with calculations based on the electrical theory. Later, Einstein from considerations of relativity showed that for any material particle, whether charged or not, the mass m must vary with speed according to the relation $m/m_0=(1-\beta^2)^{-\frac{1}{2}}$, where m_0 is the mass for low speeds, and β is the ratio of the velocity of the particle to the velocity of light. Experimental results agree closely with this calculation.

Since there must always be electric mass associated with the movement of electric charges, it is natural

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[1] From the thirteenth Kelvin lecture, delivered before the Institution of Electrical Engineers on May 18.

[2] *Philosophical Magazine*, March 1902.

to suppose that the mass of the electron is entirely electrical in origin, and no advantage is gained by supposing that any other type of mass exists. If the atom is a purely electrical structure, the mass of the atom itself must be due to the resultant of the electric mass of the charged particles which make up its structure. We shall see that only a small fraction of the mass of an atom can be ascribed to the negative electrons contained in it, but the main part is to be ascribed to the positively charged units of its structure. One of the main difficulties in our attack on the question of atomic constitution has lain in the uncertainty of the nature of positive electricity. Without entering upon the changes in point of view on this important question, it may suffice to say that the evidence as a whole supports the idea that the nucleus of the hydrogen atom, *i.e.* a positively charged atom of hydrogen, is the positive electron. No evidence has been obtained of the existence of a positively charged unit of mass less than that of the hydrogen nucleus, either in vacuum tubes or in the transformation of the radioactive atoms, where the processes occurring are very fundamental in character.

It might *a priori* have been anticipated that the positive electron should be the counterpart of the negative electron and have the same small mass. There is, however, not the slightest evidence of the existence of such a counterpart. On the views outlined, the positive and negative electrons both consist of the fundamental unit of charge, but the mass of the positive is about 1800 times that of the negative. This difference in the mass of the two electrons seems a fundamental fact of nature and, indeed, is essential for the existence of atoms as we know them. The unsymmetrical distribution of positive and negative electricity that is characteristic for all atoms is a consequence of this wide difference in the mass of the ultimate electrons which compose their structure. No explanation can be offered at the moment why such a difference should exist between positive and negative electricity.

Since it may be argued that a positive unit of electricity associated with a much smaller mass than the hydrogen nucleus may yet be discovered, it may be desirable not to prejudge the question by calling the hydrogen nucleus the positive electron. For this reason, and also for brevity, it has been proposed that the name "proton" should be given to the unit of positive electricity associated in the free state with a mass about that of the hydrogen nucleus, namely, about 1·007 in terms of O=16. A name for this unit will be found very convenient in discussing the inner structure of atoms. In the following, the term "electron" will be applied only to the well-known negative unit of electricity of small mass.

On the classical electrical theory, the mass of the electron can be accounted for by supposing that the negative electricity is distributed on a spherical surface of radius about 1×10^{-13} cm. This is merely an estimate, but probably gives the right order of magnitude of the dimensions, though it should be pointed out that in some recent theories of Compton and others it has been supposed that the electron behaves like a flexible ring, the dimensions of which are about 10^{-11} cm., or about 100 times the original estimate. Without going into these difficult questions, what little experimental evidence there is seems to me to support the older estimate of size. Taking the view based on the older theory, the greater mass of the proton is to be explained by supposing that the distribution of electricity is much more concentrated for the proton than for the electron. Supposing the shape spherical, the radius of the proton should be only $\frac{1}{1800}$ of that of the electron. If this be so, the proton has the smallest dimensions of any particle known to us. It is admittedly very difficult to give any convincing proof in support of this contention, but at the same time there is no evidence against it. From the point of view of simplicity of explanation, it is natural to make the assumption that the proton and the electron are the fundamental units of which all atoms are built.

It would take too long to consider in any detail the gradual development in the last twenty years of our ideas on the structure of atoms. Progress has depended mainly on a clearer understanding of the relative part played by positive and negative electricity in atomic structure. It is now generally accepted that the atom is an electrical system and that the atoms of all the elements have a similar type of structure.

The nuclear theory of atomic constitution has been found to be of extraordinary value in offering an explanation of the fundamental facts that have come to light, and is now generally employed in all detailed theories of atomic constitution. At the centre of each atom is a massive positively charged nucleus of dimensions minute compared with the diameter of the atom. This nucleus is surrounded by a distribution of negative electrons which extend to a distance, and occupy rather than fill a region of diameter about 2×10^{-8} cm. Apart from the mass of the atom, which resides mainly in the nucleus, the number and distribution of the outer electrons, on which the ordinary physical and chemical properties of the atom depend, are controlled by the magnitude of the nuclear charge. The position and motions of the external electrons are only slightly affected by the mass of the nucleus. According to this view of the atom, the problem of its constitution naturally falls into two parts—first, the distribution and mode of motion of the outer electrons, and secondly, the structure of the nucleus and the magnitude of the resultant positive charge carried by it. In a neutral atom the number of external electrons is obviously equal in number to the units of positive (resultant) charge on the nucleus.

The general conception of the nuclear atom arose from the need of explanation of the very large deflections experienced by swift α- and β-particles in passing through the atoms of matter. A study of the number of α-particles scattered through different angles showed that there must be a very intense electric field within the atom, and gave us a method of estimating the magnitude of the charge on the nucleus. Similarly the scattering of X-rays by the outer electrons provided us with an estimate of the number of these electrons in the atom, and the two methods gave concordant values. The next great advance we owe to the experiments of Moseley on the X-ray spectra of the elements. He showed that his experiments received a simple explanation if the nuclear charge varied by one unit in passing from one atom to the next. In addition, it was deduced that the actual magnitude of the nuclear charge of an atom in fundamental units is equal to the atomic or ordinal number when the elements were arranged in order of increasing atomic weight. On this view, the nuclear charge of hydrogen is 1, of helium 2, lithium 3, and so on up to the heaviest element uranium, of charge 92. It has been found that between these limits, with few exceptions, all nuclear charges are represented by known elements.

This relation, found by Moseley, between the atoms of the elements is of unexpected simplicity and of extraordinary interest. The properties of an atom are defined by a whole number which varies by unity in passing from one atom to the next. This number not only represents the ordinal number of the elements, but also the magnitude of the charge of the nucleus and the number of outer electrons. It could scarcely have been anticipated that, possibly with few exceptions, all nuclear charges between 1 and 92 would represent elements found on the earth. With the exception of the radio-active elements, the atoms are all stable for intervals represented by millions of years. The atomic weight of an element is not nearly so fundamental a property of the atom as its nuclear charge, for its weight depends upon the inner structure of the nucleus, which may be different for atoms of the same nuclear charge.

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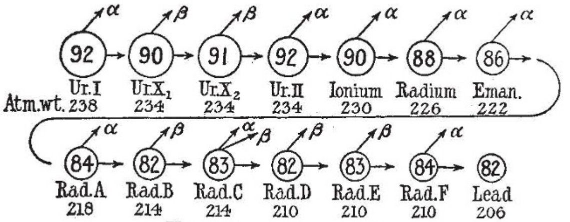
The most definite information we have of the structure of the nucleus has been obtained from a study of the modes of disintegration of the radio-active atoms. In the great majority of cases the atoms break up with the expulsion of a single α-particle which represents the doubly charged nucleus of the helium atom; in other cases a swift β-ray or electron is liberated. There can be no doubt that these particles are liberated from the nuclei of the radio-active atoms. This is clearly shown by the variation of the atomic numbers of the successive elements in the long series of transformations of uranium and thorium (see Fig. 1). The expulsion of an α-particle lowers the nuclear charge of the atom by two units and its mass by four, while the expulsion of an electron raises it by one. On this simple basis we can at once deduce the atomic number and, consequently, the general chemical properties of the long series of radio-active elements. In this way we can understand at once the appearance in the radio-active series of isotopes, *i.e.* elements of the same nuclear charge but different atomic masses.

The existence of isotopic elements was first brought to light from a study of the radio-active elements. For example, radium-*B*, radium-*D* and the end product, uranium-lead, are isotopes of lead of nuclear charge 82, but of masses 214, 210, and 206 respectively. As regards ordinary chemical and physical properties, they are indistinguishable from one another, differing only in properties that depend on the nucleus, namely, atomic mass and radio-activity. For example, radium-*B* and radium-*D* both emit β-rays, but with different velocities, while their average life is widely different. Uranium-lead, on the other hand, is non-radioactive. Many similar examples can be taken from the thorium and actinium series of elements. These illustrations show clearly that elements may have almost identical physical and chemical properties and yet differ markedly in the mass and structure of their nuclei.

From the radio-active evidence it seems clear that the nuclear structure contains both helium nuclei and electrons. In the uranium-radium series of transformations, eight helium nuclei are emitted and six electrons, and it is natural to suppose that the helium nuclei and electrons that are ejected act as units of the nuclear structure. It is clear from these results that the nuclear charge of an element is the excess of the positive charges in the nucleus over the negative. It is a striking fact that no protons (H nuclei) appear to be emitted in any of the radio-active transformations, but only helium nuclei and electrons.

Some very definite and important information on the structure of nuclei has been obtained by Aston in his experiments to show the existence of isotopes in the ordinary stable elements by the well-known positive-ray method. He found that a number of the elements were simple and contained no isotopes. Examples of such "pure" elements are carbon, nitrogen, oxygen, and fluorine. It is significant that the atomic weights of these elements are nearly whole numbers in terms of O = 16; on the other hand, elements such as neon, chlorine, krypton, and many others consisted of mixtures of two or more isotopes of different atomic masses. Aston found that within the limit of error—about 1 in 1000—the atomic weights of these isotopes were whole numbers on the oxygen scale. This is a very important result, and suggests that the nuclei of elements are built up by the addition of protons, of mass nearly one, in the nuclear combination.



Uranium-radium series

FIG 1.

[Experimental evidence was here given of the liberation of protons from the elements boron, nitrogen, fluorine, sodium, aluminium, and phosphorus. See NATURE of May 6, p. 584.]

From the radio-active evidence, we know that the nuclei of heavy atoms are built up, in part at least, of helium nuclei and electrons, while it also seems clear that the proton can be released from the nuclei of certain light atoms. It is, however, very natural to suppose that the helium nucleus which carries two positive charges is a secondary building unit, composed of a close combination of protons and electrons, namely, 4 protons and 2 electrons.

From the point of view of simplicity, such a conception has much in its favour, although it should be mentioned that it seems at the moment impossible to prove its correctness. If, however, we take this structure of the helium nucleus as a working hypothesis, certain very important consequences follow. On the oxygen scale, the helium atom has a mass very nearly 4·000, while the hydrogen atom has a mass 1·0077. The mass of the helium atom is thus considerably less than that of four free H nuclei. Disregarding the small mass of the electrons, in the formation of 1 gram of helium from hydrogen there would be a loss of mass of 7·7 milligrams.

It is now generally accepted that if the formation of a complex system is accompanied by the radiation of energy E, the reduction of the mass m of the system is given by $E=mc^2$, where c is the velocity of light. This relation between mass and energy follows not only as a direct consequence of the theory of relativity, but can be derived directly from Maxwell's theory, as pointed out by Larmor. On this relation, the energy E liberated in the formation of 1 grm. of helium from hydrogen is equal to $6{\cdot}9 \times 10^{18}$ ergs or $1{\cdot}6 \times 10^{11}$ gramme-calories. This is an enormous amount of energy, large compared even with the total energy emitted during the complete disintegration of 1 grm. of radium and its products, namely, about $3{\cdot}7 \times 10^9$ gramme-calories. It can be calculated that the energy radiated in forming one atom of helium is equivalent to the energy carried by three or four swift α-particles from radium. On this view we can at once understand why it should be impossible to break up the helium nucleus by a collision with an α-particle. In fact, the helium atom should be by far the most stable of all the complex atoms.

It has been pointed out by Perrin and Eddington that in all probability the energy of radiation from our sun and the stars is derived mainly from the enormous emission of energy accompanying the formation of helium from hydrogen. If this be the case, it is easy to show that sufficient energy can be derived from this source for our sun to radiate at its present rate for several thousand million years, whereas the older theories of Kelvin and Helmholtz, in which the heat of the sun is ascribed to the gradual concentration of the material under gravity, make the life of the sun much shorter than modern estimates of the age of the earth and appear to be quite inadequate to provide the requisite energy.

This interesting suggestion of the probable origin of the greater part of the enormous energy radiated by the sun and stars is one of the first-fruits of the investigations on the structure of atoms. It is believed that the formation of helium from hydrogen occurs under certain conditions in the great central furnace of the sun and stars, but there is no evidence, so far, that this combination can be produced under laboratory conditions. It may be that it can be effected only under conditions of very high temperature and enormous intensity of radiation such as occur in the interior of a sun. Even then the process of formation may go on at a very slow rate and for periods measured by millions of years.

Most workers on the problem of atomic constitution take as a working hypothesis that the atoms of matter are purely electrical structures, and that ultimately it is hoped to explain all the properties of atoms as a result of certain combinations of the two fundamental units of positive and negative electricity, the proton and electron. Some of the more successful methods of attack that have been made on this most difficult of problems have been indicated. During recent years, unexpectedly rapid advances have been made in our knowledge, but we have only made a beginning in the attack on a very great and intricate problem.

Great difficulties arise the moment we consider why the nucleus of an atom holds together, and progress seems likely to be slow because it seems clear that the ordinary laws of force between electrified particles break down at such minute distances. There are, however, a number of obvious lines of attack that may yield us very valuable information. In particular, a closer study of the modes of transformation of radio-active bodies, where the process of devolution of elements takes place before our eyes, may be expected to give much important data. During recent years the study of the γ- or very penetrating X-rays from radio-active bodies has progressed very rapidly. The general evidence indicates that the γ-rays, like the α- and β-particle, have their origin in the nucleus. The study of the γ-rays thus gives us information of the frequency of vibration of the electrons which form part of the nuclear structure. In addition, Ellis has shown that it appears probable that the laws of quantum dynamics which govern the motions and vibrations of the outer electrons apply also to the nuclear electrons. If this conclusion can be verified, it offers the hope that we may be able later to form some idea of the detailed structure of nuclei. There are also a number of other lines of evidence that will have to be taken into account in formulating any definite theory of the evolution of the elements; for example, Harkins has pointed out some very interesting relations that appear to exist between the relative abundance of elements in the earth and their atomic number, while the close study of stellar evolution should ultimately throw much light on the general problem.

The Royal Botanic Society's Gardens.

THE gardens of the Royal Botanic Society, Regent's Park, are one of the landmarks of London. They occupy the whole of the Inner Circle of Regent's Park, an area of nearly 20 acres. The accompanying aerophotograph shows very well their main features. The Society was established by Royal Charter in 1839, "for the promotion of botany in all its branches, and its application to medicine, arts, and manufactures, and also for the formation of extensive botanical and ornamental gardens within the immediate vicinity of the metropolis." The first president was the Duke of Richmond, and the first secretary James De Carle Sowerby, a botanist and artist, whose father, James Sowerby, was a well-known botanist in his time. The latter was author of "English Botany," a classic collection of coloured drawings of British plants, and other works. The son, James De Carle Sowerby, inherited his father's tastes as a botanist and artist. He also handed on to *his* son and grandson the office of secretary, the latter resigning shortly before the war.

Their Majesties the King and Queen and Queen Alexandra, and H.R.H. the Prince of Wales are patrons of the society, and the present President is Viscount Lascelles. The grounds of the gardens were originally