RADIUM AND THE ELECTRON.

By Sir Ernest Rutherford, F.R.S.

WHEN we view in perspective the extraordinarily rapid progress of physics during the last twenty-five years, we cannot fail to be impressed with the great significance to be attached to the discovery of X-rays by Röntgen in 1895, not only from its intrinsic interest and importance, but also from the marked stimulus it gave to investigations in several directions. In fact, this discovery marks the beginning of a new and fruitful epoch in physical science, in which discoveries of fundamental importance have followed one another in almost unbroken sequence.

It does not fall within my province to discuss the great advances in our knowledge that have followed the close study of this penetrating type of radiation, but to indicate, I am afraid very inadequately, the progress in two other directions of advance which were opened up by the discovery of X-rays, and have revolutionised our ideas of the nature of electricity and the constitution of matter.

Following Röntgen's discovery, attention was concentrated on two aspects of the problem. On the one side it was thought that the excitation of the X-rays might be connected with the phosphorescence set up in the glass of the discharge tube by the impact of cathode rays, and experiments were consequently made by several observers to test whether substances which phosphoresced under ordinary light emitted a type of penetrating X-rays. By a fortunate combination of circumstances, H. Becquerel in 1896 tried the effect of a phosphorescent uranium salt, and this led to the discovery of the emission of a penetrating type of radiation, and thus laid the foundation of the new science of radioactivity, the further development of which has been attended by such momentous consequences.

On the other side, the problem of the nature and origin of the X-rays led to a much closer study of the cathode rays and to the definite proof, as Sir William Crookes had long before surmised, that the cathode rays consisted of swift charged particles of mass small compared with that of the hydrogen atom. It was soon shown that these corpuscles of small mass or negative electrons, as they are now termed, could be set free by a variety of agencies, by the action of ultra-violet light on metals and copiously from glowing bodies, while they were ejected with high speed spontaneously from the radioactive bodies.

The interpretation by Lorentz of the Zeeman effect in which the spectrum lines were displaced by placing the source of light in a magnetic field showed that electrons of the same small mass were present in all atoms, and that their vibrations constituted visible light. Sir J. J. Thomson early pointed out the significance of the electron as one of the units of atomic structure and its importance in the mechanism of ionisation in gases, and the rapid growth and acceptance of electronic ideas owes much to his work and teaching. An important stage in advance was the proof by Kaufmann that the mass of the electron was entirely electrical in origin. Sir J. J. Thomson had shown in 1881 that a charged particle acquired additional or electrical mass in virtue of its motion. The variation of mass with speed has been shown to be in accord with general theory, but is in best agreement with the formula based on the theory of relativity. It would be of great interest to compare theory with experiment for the highest attainable speed of the electron from radium which is so near to the velocity of light that the variation of mass with velocity is very rapid.

The proof that the electron was a disembodied atom of negative electricity was a great step in advance in electrical ideas. Information as to the nature of positive electricity is far less precise and definite, for no positive electron, the counterpart in mass of the negative electron, has ever been observed. In all experiments with positive rays and with radioactive transformations where the processes are very fundamental in character, no positive charge has ever been found associated with a mass less than that of the atom of hydrogen. While it is well to keep an open mind on this fundamental question, the evidence as a whole suggests that there is an essential difference in mass between the carriers of positive and negative electricity. In fact, such a difference seems to be essential to fit in with our knowledge of the structure of atoms. The nucleus of the lightest atom hydrogen may prove to be the positive electron and its much greater mass than that of the negative electron would then be ascribed to the greater concentration of the electrical charge in the former.

From consideration of the passage of electricity through gases, it had long been surmised that electricity, like matter, was atomic in character. The study of the deflection of the cathode rays and α-rays in magnetic and electric fields showed that the carriers of each type had all the same charge, and the atomic nature of electricity was implicitly assumed by all workers. Townsend showed that the charge carried by the ions in gases was equal to the charge carried by the hydrogen atom in the electrolysis of water and made the first measurements of this fundamental unit. Other methods of attack were developed by Sir J. J. Thomson and H. A. Wilson, and by a skilful adaptation of methods Millikan was able to demonstrate in a very direct way the unitary nature of electricity and to measure the value of the unit charge, probably the most important and fundamental constant in physics, with an accuracy, it is believed, of one in a thousand. By combining the value of this constant with electrochemical data, the number of molecules in a cubic centimetre of gas and the mass of the atoms can be deduced with equal accuracy. The convincing proof of the atomic nature of electricity and the accurate measure of the fundamental atomic and molecular magnitudes are two of the greatest triumphs of the new era.

One of the most important properties of X-rays is their power of making gases a temporary conductor of electricity. The study of this small conductivity led to a clear idea of the transfer of electricity through gases by means of charged ions, and the nature and difference of the positive and negative ions have been closely studied. The proof by Townsend of the production of ions by collision in electric fields opened up a new field of investigation and gave us for the first time a clear idea of the processes leading up to an electric spark. The ionisation theory was found to explain the conductivity produced by radium rays and the conductivity of flames. The laws controlling the escape of electricity from glowing bodies were closely examined by H. A. Wilson and O. W. Richardson.

It is a striking fact that these purely scientific researches on the conductivity of gases, which had their inception in the Cavendish Laboratory, and appeared at first to have only an academic interest, should so soon have resulted in important practical applications. We may instance the use of a hot filament in a low vacuum as a rectifier of alternating currents and a detector of electrical waves. The supply of electrons from a glowing filament coupled with the generation of ions by collision has led to the production of powerful electric oscillators and amplifiers for magnifying minute currents to any desired degree. These amplifiers have not only been of great service in war, but have also rendered possible radiotelephony across the Atlantic. Last, but not least, we have the invention of the Coolidge X-ray tube, which has played such an important part in research and in radiography.

While the mechanism of ionisation of gases by X-rays and radium rays and the transfer of electricity in ordinary electric fields is in the main well understood, it is a striking fact that the passage of the disruptive discharge through a vacuum tube, which was the starting point of so many discoveries, is still almost a mystery. While no doubt some of the main factors involved in the discharge are known, the phenomena in gases at low pressure are so complex that we are still far from a complete elucidation of the problem. This complexity is well instanced, for example, by the sign and magnitude of the charges communicated to atoms and molecules in the positive rays, which have been so closely studied by Wien and Sir J. J. Thomson, and in the hands of the latter have given us a very delicate method of chemical analysis of gases in a discharge tube.

The discovery of the electron as a mobile constituent of the atom of matter has exercised a wide influence on electrical theory, and has been the starting-point of attack on numerous electrical problems. In these theories the electron may be considered as a point charge with an appropriate mass associated with it, and in many cases no assumptions as to the nature and constitution of the electron itself are involved. One of the first problems to be attacked was the passage of electricity through metals where it was supposed that the negative electrons are continuously liberated from the atoms, and are in temperature equilibrium with the matter. While the theories as initially developed by Drude and Sir J. J. Thomson have been instrumental in accounting for a number of relationships, they are unsatisfactory on the quantitative side. These difficulties have been enhanced by the recent discoveries of Kamerlingh Onnes of the supra-conductivity of certain pure metals at very low temperatures and the marked departure from the law of Ohm under certain conditions. As in the case of the theory of radiation, it may be necessary for an ultimate explanation to introduce the ideas of quanta as recently proposed by Keesom. Langevin has applied the electron theory to the explanation of magnetism and diamagnetism, but there are still many difficulties. The suggestion, first proposed by Weiss, that there exists a natural unit of magnetism called the magneton, analogous in some respects to the atom of electricity, still lacks definite confirmation.

In this brief review reference can be made only to the apparently insoluble difficulties in the explanation of the facts of radiation brought to light in recent years, and to the application of the theory of quanta which has had such a large measure of success in many directions.

Radioactivity.

The rapid growth of the subject of radioactivity after the discovery by Becquerel of the radiating power of uranium was greatly influenced by the discovery and isolation of radium in 1899 by Mme. Curie, for the radioactive properties of this element were on such a scale of magnitude that they were difficult to explain and still more difficult to explain away. The systematic chemical analysis of uranium ores disclosed the presence of new radioactive substances like polonium and actinium, while the study of thorium, radium, and actinium disclosed the emission of radioactive emanations or gases and their apparently remarkable power of conferring temporary activity on all bodies in their neighbourhood. The changes in activity of these substances with time and the different types of radiation emitted at first gave an appearance of great complexity and confusion to the rapidly accumulating mass of facts, but the whole subject took on an orderly and systematic development after the transformation theory was put forward by Rutherford and Soddy in 1903 as an explanation of radioactivity. On this view radioactive matter is undergoing spontaneous transformation of its atoms with the appearance of a succession of new radioactive bodies, each marked by characteristic chemical and radioactive properties. The radiations accompany the transformation of atoms and are a measure of the rate of transformation. Guided by this theory, the whole sequence of changes in the uranium-radium series, the thorium and actinium series, were investigated in detail, and in a remarkably brief space of time more than thirty new radioactive elements were brought to light and their position in the scheme of radioactive changes determined. Special interest attaches to the discovery by Boltwood of the substance called ionium, which is directly transformed into radium. This afforded a direct experimental method of determining the average life of radium with a result that is in close accord with the value calculated from the rate of emission of α-particles. The position of actinium in the main scheme of changes has occupied much attention. The constancy of the relative amount of actinium and uranium in uranium minerals showed that it must be derived ultimately from uranium, but the activity of actinium is too small to be in the direct line of succession. This has led to the view that actinium is a branch product at some point of the uranium series where about 6 per cent. is transformed into the actinium branch and 94 per cent. into the main line of descent. The general evidence indicates that this branching occurs near to uranium, and possibly the branch product called uranium-Y by Antonoff is the first member of the family. Recently the intermediate parent substance of actinium itself has been discovered.

While in the majority of cases the atoms of a radioactive product break up in a very definite fashion and in only one way, certain cases are known where one substance breaks into two chemically distinct substances. Examples of this are: radium C, thorium C, and actinium C. Usually the transformation is mainly in one direction with a small fraction in the side branch. It is quite probable that further study may lead to the discovery of a number of such dual transformations. In the violent cataclysm that must accompany the transformation of an atom, it is not unexpected that the constituents of the residual atom may arrange themselves in more than one configuration of temporary equilibrium.

Much attention has been directed to the properties of the radium emanation—the radioactive gas constantly produced by the transformation of radium atoms. The equilibrium volume of this gas from one gram of pure radium is only six-tenths of a cubic millimetre, but contributes more than three-fourths of the total activity of radium. By concentration of purified emanation into fine glass tubes, very powerful sources of radiation have been obtained, which have proved of great utility both in the laboratory and for therapeutic purposes. Although only about one-tenth of a cubic millimetre of purified radium emanation has ordinarily been available for experiments, methods have been devised to determine its spectrum, molecular weight, freezing and boiling points.

We owe to Hahn the discovery of two fairly long-lived products of thorium called mesothorium and radiothorium. The mesothorium, which is separated with the radium from ores containing both thorium and uranium, is transformed into radiothorium. These products can be obtained of activity greater than radium for equal weights, and give us another source of powerful radiation.

The discovery of the production of helium from radium by Ramsay and Soddy was of great importance in emphasising the reality of the transformations occurring in radium. Rutherford showed that the α-rays which are shot out from radium consist of positively charged atoms of helium so that all radioactive substances which emit α-rays give rise to helium. The production of helium by radioactive substances explains the occurrence of large quantities of helium in uranium and thorium minerals, and indeed the prediction by Rutherford and Soddy that helium would prove to be a product of radioactive transformation was based in part on this fact.

The great majority of radioactive substances are transformed with the expulsion of helium atoms with great velocity, but in a few cases swift electrons appear. The appearance of helium in so many changes, coupled with the observation that many of the atomic weights of many known elements differ by four units—the atomic weight of helium—indicates that helium must be one of the secondary units of which many of the ordinary elements are built up. It is noteworthy that so far no definite evidence has been obtained that hydrogen is a direct product of radioactive transformation, although its complete absence would be very surprising.

The proof by the Curies of the rapid and continuous emission of heat from radium showed clearly the vast amount of energy that must be stored up in radioactive matter and released by its transformation. This heat emission has been shown to be a secondary effect of radioactivity, for it is a measure of the energy of the expelled radiations, the greater part being due to the energy of the expelled α-particles.

The transformation of an atom is the result of an explosion of intense violence in which a part of the atom, whether a helium atom or an electron, is shot out with great speed. In order to produce α-, β-, or γ-rays of equal energy to those emitted by radioactive substances, potential differences of about two million volts applied to a vacuum tube would be necessary. These spontaneous radiations have been of great utility in studying the ionisation, scattering, and other properties of particles moving at high speed, while in the very penetrating γ-rays we have a type of X-rays of much shorter wave-length than can be produced at present or is likely to be produced by laboratory methods.

The properties of the α-rays have been very closely studied and their speed and mass have been determined accurately. The definiteness of the range of α-particles, to which Bragg first directed attention, is a matter of remark, and so far the apparent disappearance of the α-particle while still moving with a high velocity has not been adequately explained. The analysis of the β-rays has disclosed the presence of groups of electrons emitted at a definite velocity, so that the pencil of β-rays deflected in a magnetic field shows a veritable magnetic spectrum. The presence of these groups of β-rays appears to be connected with the emission of characteristic X-radiation from the atom, and the evidence as a whole strongly supports the view that the γ-rays from radioactive substances, like the X-rays from a vacuum tube, contain rays of a wide range of frequency in which the characteristic rays from the atom predominate.

Space does not allow me to do more than mention the extraordinary delicacy and definiteness of the electrical methods devised for measuring minute quantities of radioactive matter. By their aid the chemical properties of the numerous radioactive elements have been studied and their position in the periodic table established. The orderly sequence of changes in the chemical properties of successive elements in the radioactive series has been shown to be intimately connected with the type of radiation, whether α- or β-ray, emitted by the preceding element. One of the most important fruits of these chemical investigations has been the proof of the existence of non-separable elements, named isotopes by Soddy, which are identical in ordinary physical and chemical properties, but have different atomic weights. In the case of lead, six isotopes are already known which differ from one another either in atomic or radioactive properties. On the nucleus theory of the atom, this indicates that the charges on the nuclei are the same, but that the masses differ. The proof of the presence of isotopes promises to open up a new and very fundamental field of chemical inquiry which must inevitably exercise a great influence on atomic weight determinations and also on our ideas of atomic constitution. In a recent letter to this journal Merton has indicated that the minute change in the wave-length of spectrum lines of isotopes may give us a simple method of attack on this problem.

While the subject of radioactivity belongs in essence to the border-line of physics and chemistry, with affiliations to both sciences, it has had numerous connections with other fields of work. The examination of the earth's crust has shown that radioactive matter is very widely distributed, and has disclosed, notably through the work of Strutt and Joly, that the heating effect due to this matter vitiates to a large extent the old arguments of the duration of the earth's heat. While showing that the old views are not tenable, radioactivity has at the same time supplied new methods of estimating the age of minerals and the duration of geological epochs. The minimum age of minerals can be deduced from the helium accumulated from the transformation of radioactive matter, and the maximum age from the accumulated lead which is the product of both uranium and thorium. Now that the atomic weights of the lead isotopes are well established, the atomic weight of the lead in a uranium mineral should serve as a definite guide to the fraction of lead present which is due to the transformation of uranium and thus give a trustworthy estimate of the age of the mineral. Joly has demonstrated in a striking way that the pleochroic haloes observed in mica are of radioactive origin, and he has also estimated their age. The presence of radioactive matter in the atmosphere has been shown to account for its electrical conductivity. Just before the war, evidence was obtained indicating the presence of a very penetrating type of γ-radiation in the upper atmosphere. It is to be hoped that soon a further study will be made to determine the nature and origin of this interesting radiation. Finally, numerous investigations have been carried out to determine the effects of the radioactive rays on living tissue and on the growth of plants and organisms. With the increased use of radium for therapeutic purposes, it is likely that our knowledge of this important field of inquiry will grow rapidly.

It is a matter of remark that while the study of radioactivity has disclosed in a striking way the transformation of heavy atoms through a long series of stages, it has at the same time provided us with indubitable proof of the correctness of the old atomic theory of matter. The electric method devised by Rutherford and Geiger of counting single α-particles allows us to count the total number of α-particles projected from one gram of radium per second. By determining the volume of helium produced by the collected α-particles, we have a simple and direct method of determining also the number of molecules in a cubic centimetre of helium at standard pressure and temperature. This number is in good agreement with the number found by Millikan by measuring the charge on the atom of electricity. On account of the great energy of motion, a single α-particle can be detected in a variety of ways, by the electrical method, by the scintillations produced in zinc sulphide or the diamond, and by its action on a photographic plate.

The most striking proof of the individuality of the electron, the α-particle, and the ion has been given by C. T. R. Wilson by his beautiful photographs showing the trails of α- and β-particles through gases. By a sudden expansion, each charged ion produced by the flying particle is rendered visible by becoming the centre of a visible drop of water. In the case of the swift electron, the number of ions per centimetre of path is so small that the number may be directly counted. These photographs bring out in a vivid and concrete way the phenomena accompanying the passage of ionising types of radiation through gases, and are, in a sense, the ultimate court of appeal of the accuracy of theories of the properties of these rays.

The discovery of the electron and of the property of radioactivity has given a great stimulus to attempts to deduce the structure of the atom itself, and numerous types of model atoms have been proposed. The great difficulty in these attempts is the uncertainty of the relative importance of the *rôle* played by positive and negative electricity. In the model atom proposed by Sir J. J. Thomson the electrons were supposed to be embedded in a sphere of positive electricity of about the dimension of the atom as ordinarily understood. Experiments on the scattering of α-particles through large angles as the result of a single collision with a heavy atom showed that this type of atom was not capable of accounting for the facts unless the positive sphere was much concentrated. This led to the nucleus atom of Rutherford, where the positive charge and also the mass of the atom are supposed to be concentrated on a nucleus of minute dimensions. The nucleus is surrounded at a distance by a distribution of negative electrons to make it electrically neutral. The distribution of the external electrons on which the ordinary physical and chemical properties of the atom depend is almost entirely governed by the magnitude of the positive charge. The experiments by Marsden and Geiger on the scattering of the α-particles, and also on the scattering of X-rays by Barkla, show that the resultant units of charge on the nucleus of an element is about equal to its atomic number when arranged in order of increasing atomic weight. Strong proof of the correctness of this point of view has been given by the work of Moseley on the X-ray spectra of the elements, for he has shown that the properties of an element are defined by a whole number which changes by unity in passing from one element to the next. It is believed that the lightest element, hydrogen, has a nuclear charge of one, helium of two, lithium of three, up to the heaviest element, uranium, of charge 92.

Radioactive evidence indicates that the nucleus contains both positively charged masses and negative electrons, the positive charge being in excess. Apart from the difficulty on the ordinary laws of electric forces of explaining why the nucleus holds together, there is a fundamental difficulty of accounting for the stability of the external electrons on the ordinary laws of dynamics. To overcome this difficulty, Bohr has applied the quantum theory to define the position of the electrons and to account for the spectra of the lighter atoms and has made suggestions of the structure of the simpler atoms and molecules. Space does not allow me to discuss the important developments that have followed from Bohr's theory by the work of Sommerfeld, Epstein, and others. The generalised theory has proved very fruitful in accounting in a formal way for many of the finer details of spectra, notably the doubling of the lines in the hydrogen spectrum and the explanation of the complex details of the Stark and Zeeman effects. In these theories of Bohr and his followers it is assumed that the electrons are in periodic orbital motion round the nucleus, and that radiation only arises when the orbit of the electron is disturbed in a certain way. Recently Langmuir, from a consideration of the general physical and chemical properties of the elements, has devised types of atom in which the electrons are more or less fixed in position relatively to the nucleus like the atoms of matter in a crystal. It appears necessary, in Langmuir's theory, to suppose that electrons, in addition to their electrical charges, are endowed with the properties of a magnetic doublet, so that at a certain distance the forces of attraction and repulsion between two electrons counterbalance one another.

The whole question of the possible arrangements and motion of the external electrons in an atom or molecule still remains a matter of much doubt and speculation. While there are strong indications that the conception of the nucleus atom is in the main correct, we are still very uncertain of the laws controlling the position of the external electrons on which the ordinary physical and chemical properties depend. The study of the light spectra and also of the X-ray spectra already promise to throw new light on this very difficult but fundamental problem.

From the above hurried survey of the progress of atomic physics, it will be seen that the investigations of the past twenty-five years have dealt mainly with three great outstanding problems, viz., the nature of electricity, the structure of the atom, and the nature of radiation. While great additions have been made to our knowledge of these questions leading to a much wider outlook, we cannot but recognise that much still remains to be done before we are certain that we are building on a firm foundation for the future. Notwithstanding the prolonged halt during the war, the scientific outlook is one of good augury for the immediate future, and there is every prospect that the vigorous attack on these outstanding problems will be continued.

ATOMS AND MOLECULES.

BY PROF. FREDERICK SODDY, F.R.S.

IT may be doubted whether, fifty years ago, chemists and physicists believed very deeply in the actual reality of the molecules and atoms, which they used as convenient and simplifying conceptions to interpret the behaviour of matter. The half-century, indeed, has not passed without strong protest from the thermodynamical school of physical chemistry that the science should be so wedded to pure hypotheses and unverifiable assumptions, then, apparently, for ever beyond the power of being actually apprehended and demonstrated. That the modern student of physical science believes in the reality of the existence of his atoms and molecules, as much as he does in that of chairs, tables, and lamp-posts, probably sufficiently epitomises one of the