rocks can now be accurately measured. In 1929 the writer pointed out that "since igneous rocks suitable for the helium method are far more abundant and far better distributed in time than are radioactive minerals suitable for the lead method, there is now available a practical means of effecting long-distance correlations and of building up a geological time scale which, checked by a few reliable lead-ratios here and there, should become far more detailed than could ever be realised by means of the lead method alone". In the accompanying table some of the results which have since been obtained by Paneth, Dubey and Urry are listed.

The oldest minerals so far reliably dated by the lead method are those of Manitoba, to which reference has already been made. A similar age of more than 1,700 million years has recently been found for zircons from a South Dakota granite, which itself is older than the South Dakota uraninite analysed by Davis (1,465 million years). At least one cycle of sedimentation preceded the intrusion of these oldest known granites of North America, and by analogy with other such cycles, this would seem to indicate that the age of the earth cannot be less than 1,900 million years. No approach to a closer estimate is practicable at present. It is not improbable that a maximum limit may be set by the age determinations of meteorites made by Paneth and his colleagues. The results range up to 2,800 million years, but while the origin of meteorites remains in doubt the significance of these figures remains speculative. It appears possible, however, that the earth, the solar system and the present organisation of the stellar universe may all be of the same order of age, namely, 2,000–3,000 million years.

To geologists, the exact age of the earth is of less importance than the application of age measurements to dating igneous rocks, correlating Pre-Cambrian formations in various parts of the world, and building up a reliable time-scale. With the aid of the latter it is becoming possible to estimate the rates at which various geological processes have operated in the past. It is already clear that, at least during the later part of geological time, there has been a remarkable acceleration of activity, and that during the Tertiary period, in particular, the earth was more vigorous in its behaviour than at any other time since the late Pre-Cambrian.

Atomic Physics

By THE RIGHT HON. LORD RUTHERFORD, O.M., F.R.S., Cavendish Professor of Physics, University of Cambridge

THE past twenty-five years has been a period of unexampled activity in physical science, and has witnessed a series of important discoveries which have widely extended our knowledge of the nature of the atoms and the interaction between matter and radiation. On looking back, we can see that the direction of advance was greatly influenced by three fundamental discoveries made at the end of last century—the discovery of X-rays, of radioactivity and of the electron. The proof of the wave-nature of the X-rays in 1913 led to the development of simple methods for studying the X-ray spectra of the elements, and thus gave us important information on the arrangement of the electrons deep in the atom and their frequency of vibration. The study of the radioactive bodies had disclosed that they were undergoing spontaneous transformation and gave us for the first time an idea of the enormous forces which must exist within the structure of the atom. Sir J. J. Thomson early recognised that the electron must be a fundamental constituent in the structure of all atoms, and had devised methods for estimating the number of electrons present in each atom.

The nuclear theory of the atoms, based on experimental evidence of the scattering of α-particles by matter, belongs to the beginning of the period under review. The proof by Moseley that the properties of an atom are defined, not by its atomic weight, but by its atomic or ordinal number, was an outstanding step in advance. It was shown that the atomic number was a measure of the number of units of resultant charge carried by the nucleus and also a measure of the number of electrons surrounding the nucleus. A relation of extraordinary simplicity was thus seen to connect all the elements—a relation which has governed all subsequent advances in our knowledge of the elements.

The proof that the chemical elements are complex and in general consist of a number of isotopes of different masses was an important advance. This conception, which we owe to Soddy, had its origin in the study of the chemical properties of the radioactive elements. In the nuclear theory, isotopes represent atoms of identical nuclear charge but different masses. They should have the same chemical properties, apart from mass, and almost identical spectra. Ashton showed in 1919 that the masses of the individual isotopes were nearly whole numbers in terms of O = 16. This whole number rule, while very convenient as a guide, is only approximate. The accurate determination of the masses of the isotopes is of first importance, for it serves in a sense as a measure of the energy stored up in the atom and thus enters into all calculations which have to do with the transmutation of atoms.

More than 250 species of atoms are now known, and even the lightest atom—hydrogen—has been shown in the last few years to consist of three isotopes of masses 1, 2 and 3. The isotope of mass 3 was first observed by Oliphant in transmutation experiments and has since been found to be present in ordinary hydrogen in about one part in a hundred million. The discovery of the isotope of mass 2, now called deuterium, by Urey, has had important consequences, since it can readily be separated in a nearly pure state, and made use of in many physical and chemical experiments.

This period has also seen the beginning and ultimate success of the application of quantum ideas to the explanation of the origin of the spectra of the elements, both X-ray and optical. This wonderful advance, which we owe largely to the work of Bohr, is one of the most spectacular triumphs of this age. Within less than a decade, the intricacies of the varied spectra of the elements were unravelled and explained along general lines. At the same time, there followed a complete understanding of the underlying meaning of the periodic table of the elements by taking into account the way in which electrons are grouped round a nucleus.

The application by Bohr of the quantum theory for the explanation of spectra was at first beset with many difficulties and ultimately led to the development of a new mechanics—the wave-mechanics—so closely associated with the names of de Broglie, Heisenberg, Schrödinger, Born and Dirac. This has proved successful in giving an explanation not only of the complexities of the spectra of the elements but also of many of the most recondite problems of atomic physics. It has been applied to account in a general way for certain radioactive relations like the Geiger-Nuttall rule, while Gamow has utilised the theory to account for the artificial transformation of elements by particles of very low speed which on classical mechanics had no possibility of entering a nucleus.

The essential correctness of the ideas underlying the wave-mechanics has been verified by the direct experiments of Davisson and Germer, G. P. Thomson and Stern, by observing the diffraction effects produced by electrons and atoms when they fall on a crystal.

It will be seen that the past twenty-five years has been mainly occupied in an intensive study of the properties and structure of the atoms of the elements. An enormous new territory of knowledge has been opened up and surveyed in detail. While the first idea of the quantum theory of radiation had been advanced by Planck in 1905 to account for the distribution of energy in the spectrum of a hot body, it was not until the period under review that the full significance and fruitfulness of the new conception was generally recognised. It was early applied by Einstein to explain the photo-electric effect and by Nernst and Debye to account for the variation of specific heat with temperature, but its full importance was not realised until Bohr's work on the origin of spectra. The interchange of energy between a quantum and an electron was made clear, while the interaction with an electron, which gives rise to scattering, was examined and explained by Compton on the quantum theory.

Another strange type of interaction between radiation and matter has recently been discovered. When a gamma-ray of high quantum energy interacts with the intense electric field near a nucleus, the energy of the gamma-ray may be transformed with the appearance of an electron pair—one positive and the other negative. Since the mass energy of the electron pair is about one million volts, this type of interaction only occurs when the quantum energy of the gamma ray exceeds this value. The passage of high-frequency radiation through matter of high atomic weight is one of the simplest ways of producing positive electrons for study in the laboratory.

Only brief reference can be made to two important problems which have occupied the attention of many investigators throughout the world during the last few years, namely, the cosmic rays and the transformation of matter. The existence of a very penetrating radiation in our atmosphere was first shown by Kolhörster, and the properties of this radiation have been examined by Millikan, Clay, A. H. Compton, Blackett and many others. When we consider the minuteness of the ionising effect of this radiation in an electroscope near the earth, much skill and technical ability have been required to make accurate observations often under difficult conditions. The investigations have been world-wide, and have involved measurements in deep water, on land and sea, on high mountains and at different heights in our atmosphere, extending far into the stratosphere.

It now seems likely that the main radiation consists of a stream of fast electrons, both positive and negative, possibly also protons with an admixture of high-frequency radiation. It is believed that some of the particles have energies so high as 10^9 volts and a few as high as 10^{10} volts —energies of a different order of magnitude from those to be expected from the transformation of atoms. Naturally there has been much speculation as to the origin and nature of this extraordinary radiation, which appears to come either from the confines of our atmosphere or from the depths of outer space. The conditions under which particles can reach such gigantic energies constitute one of the outstanding unsolved problems of physics.

While the natural transformation of the radioactive elements was made clear in 1903, the proof of the transmutation of many of the stable chemical elements by artificial methods belongs to the past quarter of a century. The study of these transformations has been very fruitful, leading to the discovery of three important entities in the structure of the atom—the proton, neutron and the positron, the counterpart of the negative electron of small mass.

In order to produce a veritable transformation of an element, it is necessary to change its nuclear charge or its mass or both together. The chief method employed for this purpose is to bombard the element under examination by fast particles like protons, neutrons or α-particles. Occasionally one out of a great number of these particles may happen to penetrate a nucleus and be captured by it. The resulting nucleus may be unstable and break up with explosive violence, hurling out a fast particle or particles, and sometimes emitting high-frequency radiation. The residual nucleus may be either a stable element or an unstable element which behaves like a radioactive body. The production of artificial radioactive bodies in this way by α-particle bombardment was recently observed by M. and Mme. Curie-Joliot.

The first successful experiment on transmutation was made in 1919 when nitrogen, bombarded by α-particles, was found to be transformed with the emission of fast protons. Rutherford and Chadwick found that about a dozen of the lighter elements suffered a similar type of transformation under the same conditions. In order to extend these observations, investigations were begun, often on a large scale, to produce intense streams of fast particles of different kinds to be used for bombarding purposes. Cockcroft and Walton first showed that marked transformations could be produced in the light elements lithium and boron when they were bombarded by streams of fast protons accelerated in a discharge tube. Lawrence, in California, used an ingenious method of obtaining fast particles by multiple acceleration in a magnetic field, and was able to obtain swift particles of energies as high as two million volts. He found that the ions of heavy hydrogen of mass 2 were even more effective than protons in producing new types of transformation in a number of elements. In some cases, neutrons as well as protons and α-particles appeared as a result of the transformations.

The discovery of the neutron by Chadwick has proved of great importance not only in simplifying our ideas of the structure of nuclei but also as an extraordinarily effective agent in bringing about the transformation of many elements, as was first shown by Feather and Harkins. Fermi and his co-workers, in Rome, made an important advance when they showed that neutrons could enter freely into the structure of even the heaviest nuclei, in many cases leading to the production of artificial radioactive bodies which broke up at a characteristic rate with the emission of fast negative electrons. More than fifty of these radioactive bodies are now known.

By these transformation methods, it has been found possible to build up heavier atoms from lighter, to break some atoms into fragments, and to produce radioactive isotopes in great numbers. New and unsuspected stable isotopes of the elements, like H^3, He^3 and Be^8, have been brought to light, and gamma-rays of much higher frequency than those from the natural radioactive bodies have been observed.

The rapid advance of our knowledge of nuclear transformations has been in no small part due to the development of new technical methods of attack; for example, the automatic method of counting α-particles and protons devised by Wynn Williams, the Geiger-Müller tube for recording positive and negative electrons, and that wonderful instrument, the cloud chamber, devised by C. T. R. Wilson. The development of fast diffusion pumps by Gaede has made possible the rapid production of high vacua and the application of high potentials to discharge tubes.

Our ideas of the structure of atomic nuclei are still in a very tentative state, but it is generally believed that the proton and neutron are the primary building units. The exact relation, if any, between the proton and neutron is still uncertain. Some believe they are mutually convertible in a nucleus by the gain or loss of an electron, and that even negatively charged protons may be formed. Much more information is required before we can hope to reach a satisfactory explanation of nuclear structure, and any detailed theory applicable to the nucleus is probably far distant.