Radioactivity and Radioactive Substances

CHADWICK

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RADIOACTIVITY AND RADIOACTIVE SUBSTANCES

AN INTRODUCTION TO THE STUDY OF RADIOACTIVE SUBSTANCES AND THEIR RADIATIONS. THE NATURE OF RADIOACTIVITY AND THE BEARING OF RADIOACTIVE TRANSFORMATIONS ON THE STRUCTURE OF THE ATOM

BY

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WITH FOREWORD BY

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Revised and Reprinted

PITMAN'S TECHNICAL PRIMERS

LONDON
SIR ISAAC PITMAN & SONS, LTD.
PARKER STREET, KINGSWAY, W.C.2
BATH, MELBOURNE, TORONTO, NEW YORK
1923

PRINTED IN BATH, ENGLAND
BY SIR ISAAC PITMAN AND SONS, LTD.

FOREWORD

I HAVE read with pleasure this little book of my friend Dr. J. Chadwick. It is a clear and accurate account of radioactive phenomena written by one who has a first-hand knowledge of the facts. For the beginner, the treatment of the subject gains in clearness by using, as the author has done, the modern conceptions of atomic structure and by disregard of the historical order of discovery. To all those who are interested in the development of our knowledge of this fascinating subject I can strongly recommend this book as a simple, concise, and accurate statement of the main facts and theories.

E. RUTHERFORD.

CAVENDISH LABORATORY,
June, 1921.

AUTHOR'S PREFACE

The study of the radioactive elements is in some respects far more important than the study of the ordinary stable elements, for the phenomena observed lead at once to the necessity of an atomic structure of matter and supply convincing proof of the individual existence of atoms. The processes of radioactive transformations are indeed of fundamental nature; they throw light on the detailed structure of the atom, the problem which lies at the basis of physics and chemistry.

In this book an endeavour has been made to emphasize the fundamental nature of the transformations by their immediate presentation as a disruption of the atomic nucleus, rather than to preserve a logical appearance by means of a historical development. The nuclear theory of atomic structure has been confirmed by such varied evidence that no doubt of its essential truth can be entertained.

It affords a direct explanation of most of the important facts of radioactivity; for example, the chemical properties of the radioelements and the nature of isotopes follow immediately.

This method of presentation has the further advantage that the reader is provided from the beginning with a mental picture of an atom, and is able to visualize the phenomena.

In the small compass of this book it is impossible to do more than sketch the main outlines of the subject. Much important detail has been omitted, but, where practicable, attention has been paid to quantitative agreement between theory and experiment.

The reader desiring a full account of the subject of radioactivity is advised to read Rutherford's *Radioactive Substances and their Radiations.*

J. CHADWICK.

CAMBRIDGE.

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RADIOACTIVITY AND RADIOACTIVE SUBSTANCES

CHAPTER I

THE NATURE OF RADIOACTIVITY

1. Introduction. The discovery by Becquerel, in 1896, of that property of matter now termed radioactivity opened up a new and important field of enquiry. Becquerel found that uranium salts emitted spontaneously a radiation which was capable of passing in varying degrees through all matter, whether transparent or opaque to light, and which could be detected by its effect on a photographic plate. The radiation from uranium also possessed the property of imparting electrical conductivity to air and other gases, and this supplied a powerful method of detecting and measuring such radiations. The further investigation of the radioactivity of uranium resulted in the discovery of many new substances, some of which exhibited this property to such an extraordinary degree that their presence was disclosed by their radioactivity, the quantity of these substances being too small to be detected by any other means.

At the present time nearly forty radioactive elements are known, each with a definite and characteristic kind of radioactivity. Two of these, uranium and thorium, were known in 1896, and were at the end of the Periodic Table, having atomic weights of 238 and 232 respectively. Between these elements and the next heaviest, bismuth (208), there was a large gap. This is now filled by the radioactive elements.

The study of these elements and of their radiations proved to be of great interest and importance, and it is safe to say that the greater part of our knowledge of the atom has resulted from it. Not only has this study supplied experimental evidence of the individual existence of the atom as a definite unit in the structure of matter, but it has shown that the atom itself is a complex structure, consisting of negatively and positively charged particles, and it has indicated the main lines of this structure.

2. Radioactive Substances and their Radiations. A radioactive substance may be defined as one which possesses the property of emitting spontaneously radiations capable of passing through sheets of metal and other substances opaque to light. These radiations act similarly to light on a photographic plate, cause marked fluorescence in certain substances, and impart electrical conductivity to the air.

This is, however, not quite a rigorous definition of the term "radioactive." It is possible that an ordinary element could be made to simulate to some extent the above properties, e.g. by causing it to emit short ultraviolet rays. The distinction lies in the nature and origin of the radiations emitted by the radioactive elements.

These radiations will be shown later to be for the most part corpuscular in nature, consisting of material particles projected from the substance with great velocity. There are three distinct types known as the alpha, beta, and gamma rays (α, β, γ). The *α-rays* consist of a stream of positively charged particles, each of which has a mass four times that of the hydrogen atom and a positive charge of two electronic units. It is, in fact, an atom of helium with two positive charges. The *β-rays* are also corpuscular in nature, being negative electrons moving with high velocity. They are similar to the cathode particles in a discharge tube. The *γ-rays* are of secondary importance, being regarded as an accompaniment of the emission of α- and β-particles. They are similar to X-rays.

A radioactive substance may now be defined as one which emits spontaneously an α- or β-radiation.

3. The Transformation Theory. In order to explain the phenomena of radioactivity, Rutherford and Soddy put forward the transformation theory. According to this theory the atoms of a radioactive substance are undergoing a process of spontaneous disintegration, giving rise to the formation of a new atom, distinct in physical and chemical properties from its parent. The α- or β-particles emitted are parts of the disintegrating atom, and afford a measure of the rate at which the atoms are breaking up. The new atom is in its turn unstable, and breaks up with the emission of a characteristic type of radiation. This process of transformation continues through a number of definite stages, which have been followed and analysed in detail, the radiations serving as a measure of the rate of disintegration.

As an example of the process, consider the case of radium. Radium transforms slowly compared with most radioactive bodies; about one atom in 10^{11} breaks up each second, or half the atoms of an amount of radium are transformed in 1,800 years. The radium atom disintegrates with the expulsion of an α-particle. The residual atom is an atom of radium emanation, a heavy monatomic gas, which is half transformed in 3·85 days. The transformation of the emanation is accompanied by the emission of an α-particle, and the resulting product is radium *A*, a solid, which is very unstable, being half transformed in 3 minutes. These transformations are represented graphically in Fig. 1.

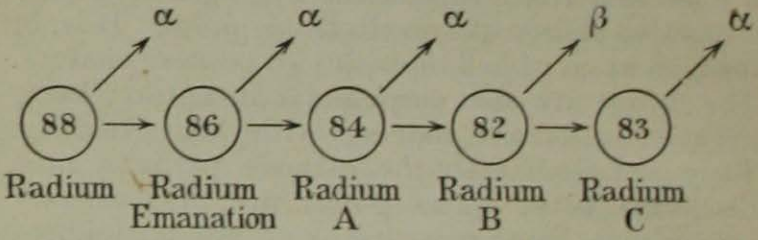

FIG. I.—THE TRANSFORMATIONS AND EMISSIONS OF RADIUM AND ITS PRODUCTS

The process of successive transformations continues through a number of further stages, each accompanied by the emission of some type of radiation. Each one of these substances is to be regarded as a new element, with its own physical and chemical properties.

The transformation theory accounts in a satisfactory way for all the known facts of radioactivity, and has predicted numerous quantitative results which have been verified by experiment.

4. Difference between Radioactive Changes and Chemical Changes. Radioactive changes are quite different from ordinary chemical changes, for they deal with the disruption of the atom while chemical changes deal with the dissociation of molecules into atoms and the modes of combination of the atoms. The radioactive processes are spontaneous and uncontrollable, and are entirely unaffected by physical and chemical agencies. The rate of transformation of a radioactive substance is the same at the temperature of liquid air, −186°C, as at a temperature of 2,000°C, and is the same in a vacuum as under a pressure of 2,000 atmospheres. Also, it is not changed in any way by subjecting the substance to chemical processes.

These facts show clearly the difference between the atomic transformations dealt with in radioactivity and the ordinary molecular reactions of chemical changes.

The amount of energy liberated in the form of radiation during the disintegration of the active bodies is very large compared with that accompanying molecular changes. The energy of the radiations is converted finally into heat, and the rate of emission of heat of the radium products has been accurately measured. It is found that the energy emitted by a radioactive substance which expels α-particles is several million times greater than the energy emitted by an equal weight of matter in any known chemical reaction. This energy is derived from the energy stored up in the atom itself, either in kinetic or potential form. The radioactive processes thus reveal an enormous store of energy resident in the atoms. No indications of this had been observed previously, because the chemical and physical forces at our disposal were not sufficient to cause atoms to break up into simpler forms.

The nuclear theory of atomic structure, described in the next section, involves the necessity of a large store of energy in the atom, and throws an interesting light on the nature of the change which a radioactive atom undergoes on transformation.

5. The Nuclear Theory of the Atom. Evidence from a variety of sources has led to the conclusion that all atoms consist in part of negatively electrified particles, the electrons. Since the atom, as a whole, is neutral, there must be a positive charge associated with the atom equal in amount to the sum of the negative charges. The electrical forces between the positive and negative charges preserve the equilibrium of the atom. In order to account for the scattering of α-particles (*see* § 31), Sir Ernest Rutherford suggested that the positive charge of the atom is concentrated in a minute volume or nucleus. This is surrounded by a distribution of negative electrons extending over a distance comparable with the diameter of the atom, as ordinarily understood. Fig. 2 gives a rough idea of the general build of the nucleus atom.

Since the negative electrons have a very small mass, by far the greater part of the mass of the atom is resident in the nucleus. The magnitude of the positive charge on the nucleus must, since the atom is neutral, be equal to the sum of the charges of the negative electrons, that is, equal to Ne where N is the number of these electrons, and e the electronic charge. It is found that the number N is given by the atomic number of the element, i.e. the number of the place the element occupies when all the elements are arranged in order of increasing atomic weight.

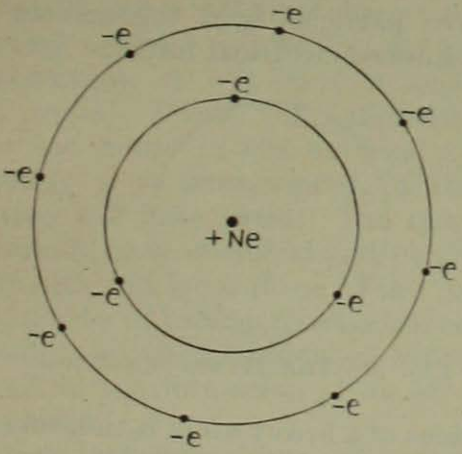

FIG. 2.—THE NUCLEUS ATOM

Thus the hydrogen atom consists of a very small nucleus of unit positive charge attended by one electron (Fig. 3). The hydrogen nucleus is the unit of positive electricity, and all nuclei are believed to be built up in some way from hydrogen nuclei and electrons. For example, the heliūm nucleus has a mass 4 ($H = 1$) and a charge of 2 units. On this theory, it will, therefore, contain four hydrogen nuclei, bound together by two electrons.

It is clear that the nucleus of a heavy atom must be an exceedingly complicated structure, consisting of a large number of these positive and negative particles held together in a small volume by intense electrical forces.

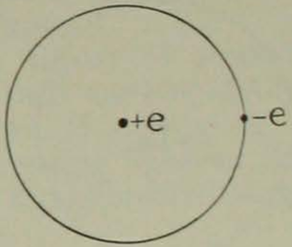

FIG. 3.—THE HYDROGEN ATOM

The nucleus of a heavy atom is thus an enormous reservoir of energy. The gold atom, for example, has a mass of 197 ($H = 1$) and a nuclear charge of 79 units. The nucleus will be built up in some way from 197 hydrogen nuclei and 118 electrons.

On this conception, the most important characteristic of an atom is the magnitude of its nuclear charge. The physical and chemical properties of an atom depend entirely upon the number and arrangement of the electrons around the nucleus, and obviously this is decided by the value of the charge on the nucleus. The mass of the nucleus influences the arrangement of the electrons only to a very small degree.

The fundamental constant of an atom is, therefore, its nuclear charge and not its atomic weight.

6. The Nature of Radioactive Changes. We are now in a position to appreciate the nature of the change which takes place when an atom disintegrates. On the nuclear theory, the α-particle emitted by a radioelement must have its origin in the nucleus of the atom. Since the α-particle has a mass 4 and a positive charge of two units, the residual nucleus will be lighter and, what is more important, it will have a smaller charge by two units. There will, therefore, be two electrons too many in the external system, and consequently a re-arrangement of this external distribution will take place. The resultant atom will, therefore, have chemical and physical properties quite different from those of the parent atom.

The majority of radioactive transformations are accompanied by the emission of α-particles, and thus result in the formation of an atom of lower nuclear charge.

The other transformations are accompanied by the expulsion of β-particles. In these changes an electron escapes from the nucleus with high speed. The residual nucleus has, therefore, practically the same mass as its parent, but its charge has increased by one unit, giving an atom of totally different properties.

In Fig. 1 the actual atomic numbers, or values of the nuclear charges in fundamental units, are given in the circles representing the atoms.

The nature of the occurrence which causes the nucleus of a radioactive atom to break up is as yet quite unknown. The observed relations of radioactive changes show that the occurrence is of a very complicated nature, and is governed by the laws of chance (§ 40).

CHAPTER II

THE IONIZATION OF GASES

7. The Ionization Theory. The most important property of the radiations from radioactive bodies is their power of ionizing a gas, i.e. of causing it to conduct electricity. This property forms the basis of the chief method for analysis and comparison of the radiations. It is necessary, therefore, to consider briefly the processes concerned in the conduction of electricity through gases.

These processes are explained on the assumption that the radiations in their passage through a gas produce positively and negatively charged carriers. The rate of production of these carriers, or ions, as they are called, is proportional to the intensity of the radiation. The ions, under the action of an electric force, move with uniform velocity, the magnitude of this velocity being proportional to the value of the electric force.

Suppose that a gas between two metal plates A and B (Fig. 4) is exposed to the radiations from active matter placed on A. A certain number of ions will be produced per second by the radiations, this number depending upon the properties of the radiations and of the gas. The total charge on all ions of one sign is equal and opposite to that on all ions of the other sign. Now, if an electric field be applied between A and B, the positive ions will move towards the negatively charged plate B, and the negative ions will move towards the positive plate A. The ions will finally reach the plates and give up their charge to them. Thus, a current will pass through the gas.

8. Recombination and Diffusion of Ions. When no electric field is acting, the number of ions in a gas exposed to radiations will not increase indefinitely, but will reach a limiting value owing to the processes of recombination and diffusion. Oppositely-charged ions attract one another and re-combine to form neutral systems which are no longer effective in conduction. The rate at which recombination proceeds depends on the number of collisions between oppositely-charged ions, and this is proportional to the square of the number of ions present. When no electric field is applied to remove the ions to the electrodes, a state of equilibrium is reached when the rate of production of ions by the radiation is equal to the rate of recombination. If the source of radiation is removed, recombination proceeds until all the ions have disappeared; the gas then ceases to conduct electricity.

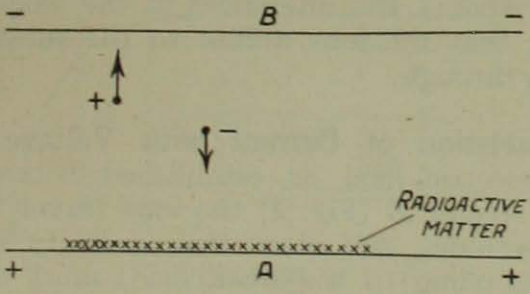

Fig. 4.—Electrical Conductivity of Gas due to Ionization

As an illustration of the rate of recombination, suppose that there are 10^6 ions in each cubic centimetre of gas at the moment the radiation is cut off; half of these ions re-combine in 0·7 secs., and 99 per cent. recombine in 70 secs.

Some ions will also disappear by a process of diffusion to the sides of the containing vessel, where they give up their charge. The rate of diffusion is slow, and this effect is generally small, compared with the disappearance of ions by recombination, unless the volume of the gas is very small. For example, the ions may be removed from a gas by passing it through a plug of cotton wool; the interstices in the wool are so narrow that the ions diffuse to the sides before passing through.

9. Variation of Current with Voltage. If a weak electric field be established between the plates *A* and *B* (Fig. 4) the ions travel towards the electrodes, but since their velocity is small (corresponding to the weak field) most of them recombine on the way. The current through the gas is consequently small. Since the velocity of the ions is directly proportional to the strength of the electric field, as the field is increased a smaller number of ions recombine on their way to the plates and the current increases. A maximum value of the current is reached when the electric field is sufficiently strong to remove all the ions before appreciable recombination has occurred. Even though the voltage be increased greatly, the current then remains constant, for all the ions produced in the gas are removed to the plates. This maximum current is called the "saturation current," and the voltage necessary to obtain it is called the "saturation voltage." The general shape of the current-voltage curve is shown in Fig. 5.

It is clear that the saturation current through an ionized gas measures the rate of production of the ions, and therefore the intensity of the ionizing radiations. The electrical method of examining and comparing the radiations from radioactive substances consists in the measurement of this saturation current. The methods used to measure the saturation current are described in the next chapter.

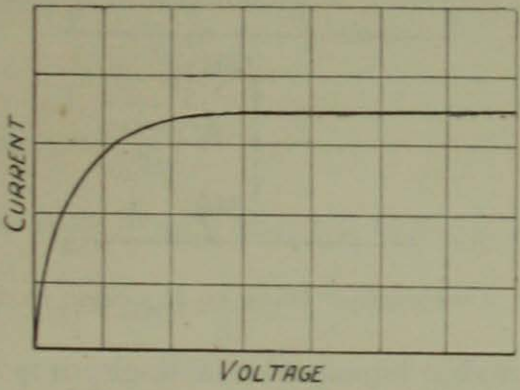

FIG. 5.—SATURATION CURVE FOR CURRENT FLOW THROUGH AN IONIZED GAS

10. Charge on the Ions. The most important characteristic of an ion is its electrical charge. The measurement of this charge was made possible by the discovery that the ions serve as nuclei for the condensation of water. If air saturated with water vapour be expanded suddenly, the air is cooled, and a cloud of small drops of water is formed. These drops form round the dust particles present in the air. If these dust particles be removed, it is possible to have a considerable expansion of the saturated air without the formation of a cloud of drops. C. T. R. Wilson found that in this respect the gaseous ions behave like dust particles. Each ion becomes the centre of a minute globule of water, and the number of drops formed is equal to the number of ions present.

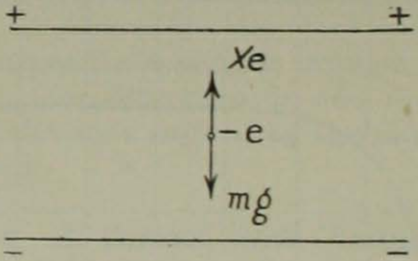

FIG. 6.—CHARGED DROP IN ELECTRIC FIELD

With suitable illumination a single drop can be observed under the microscope. The drop will fall under the gravitational force and, since it is very small, its velocity will be uniform. From the velocity we can deduce, by Stokes' Law, the size of the drop.

Now suppose that the drop is included between two parallel plates, between which a strong electric field can be established (Fig. 6). There will now be an electric force on the drop, which will increase or decrease its rate of fall according to the direction of the field. Measurements of the rate of fall under these conditions, combined with the previous measurement of the fall under gravity, enable the value of the charge on the drop to be found.

For example, suppose that in an electric field of strength X the drop is stationary, i.e. the electric force on the drop exactly balances the weight. Then—

$$Xe = mg$$

where e represents the charge, and m the mass of the drop. From Stokes' equation, the velocity v of a drop of radius a and density p falling under gravity through a gas, of which the coefficient of viscosity is u, is given by—

$$v = \frac{2}{9}\frac{pga^2}{u}$$

$$\text{whence } a = \left(\frac{9uv}{2pg}\right)^{\frac{1}{2}}$$

$$\text{Now } m = \frac{4}{3}\pi a^3 p \text{ and, for water, } p = 1.$$

$$\text{Hence } Xe = mg = \frac{4}{3}\pi\left(\frac{9uv}{2g}\right)^{3/2}$$

and all the quantities necessary to determine e are known.

In this way it was found that the smallest charge on a negatively charged drop was the same as the smallest charge on a positively charged drop. Some drops had larger charges, but the charge was always a multiple of this smallest charge, e. These drops were no doubt formed by the coalescence of two or more drops. This charge e is the charge of the electron, and has been measured by Millikan, who found that its value is $4{\cdot}77 \times 10^{-10}$ electrostatic units.

11. Mobility of the Ions. The mobility of the ions, i.e. the velocity of the ions under a potential gradient of 1 volt per cm., has been measured by different methods with concordant results. It is found that, at pressures greater than a few millimetres of mercury, the velocities of the ions are proportional to the strength of the field. When a field is applied the ions almost instantly attain the velocity corresponding to the strength of the field, and then move with uniform velocity. The mobility of the ions depends on the nature of the gas in which they are produced and on its pressure. In air at atmospheric pressure the mobility of the positive ion is about 1·4 cm. per sec., and of the negative ion about 1·8 per cm. per sec., while the mobilities in hydrogen are respectively 6·7 cm. per sec. and 7·9 cm. per sec. The mobility of the negative ion is generally greater than that of the positive ion. The mobility of the ions is inversely proportional to the pressure of the gas. At pressures below 10 cm. of mercury, however, the mobility of the negative ion increases very rapidly, indicating that on the average its mass is decreasing.

12. Nature of the Ions. Measurements of the rate of diffusion show that the ions diffuse very slowly, as if their mass were large compared with that of a molecule of the gas in which they are produced. It was accordingly suggested that the ion consisted of a cluster of molecules. The general evidence, however, is against this view, and indicates that the ion is usually a single molecule. The slow rate of diffusion and the small mobility are probably due to the charge carried by the ion; the resulting attraction of the ion for neutral molecules and oppositely charged ions diminishes its rate of progress through the gas.

The evidence suggests that the process of ionization in gases consists in the removal of an electron from the molecule of the gas. The residual molecule is charged positively and forms the positive ion. At ordinary pressures the detached electron becomes attached almost instantly to a neutral molecule, forming a negative ion of the same size as the positive ion. Thus, at ordinary pressures both kinds of ions have much the same mobility; the greater mobility of the negative ion is due to the great speed which it acquired during the very short period in which it was unattached to a molecule. At low pressures the negative electron may exist for some time without colliding with a molecule and becoming attached to it. During this time it will acquire a considerable velocity. It is to be expected, therefore, that the mobility of the negative ion will be abnormally high at such pressures, and experiment shows that this is the case.

13. Ionization by Collision. Since the radiations from radioactive bodies consist of charged particles moving with high velocity, we should expect that the ions in a gas would themselves possess the power of ionizing if caused to move with sufficient velocity. This effect of ionization by collision of the ions with gas molecules is, in fact, observed at low pressures.

If the increase of current with voltage is determined for an ionized gas at a pressure of a few millimetres of mercury, a curve is obtained of the general shape shown in Fig. 7. The portion *O A B* corresponds to the ordinary saturation curve. As the electric field is increased beyond a certain value, depending upon the pressure and nature of the gas, the current begins to increase very rapidly and ultimately a spark passes.

This increase is due to the production of fresh ions by the collision of the negative ions with the gas molecules. As the electric field approaches the sparking value the positive ions also acquire sufficient velocity to produce ions by collision, but generally their effect is small compared with that of the negative ions.

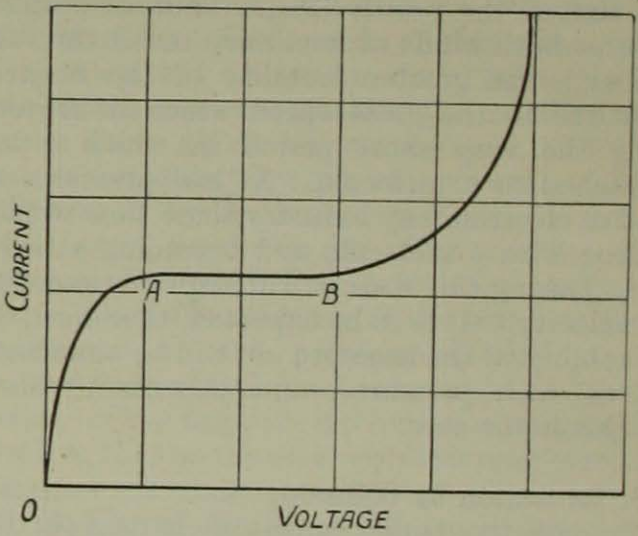

FIG. 7.—CURRENT-VOLTAGE CURVE FOR GAS AT LOW PRESSURE, SHOWING EFFECT OF IONIZATION BY COLLISION

This phenomenon affords a means of magnifying small ionization currents, for, by adjusting the voltage and the pressure, the number of ions produced in a gas can be multiplied many thousand times by collision. In this way it is possible to detect a single α- or β-particle by its electrical effect.

14. Number and Distribution of the Ions. The number of ions produced per second in a gas is generally minute compared with the number of molecules present. With a sensitive electroscope it is possible to measure a production of 1 or 2 ions per cu. cm. per sec. in a volume of 1 litre. Since the number of molecules in 1 cu. cm. of air at N.T.P.* is $2{\cdot}7 \times 10^{19}$, this corresponds to an ionization per sec. of about one molecule in 10^{19}. Under ordinary conditions of experiment, when active sources are compared by their radiations, the fraction of molecules ionized per second will not be more than 1 in 10^{14}.

The ions produced by the radiations from radioactive substances are not distributed uniformly throughout the volume of the ionized gas. The α-particles travel in straight lines, and produce a very intense ionization along their path. The number of ions produced depends on the speed of the α-particle and, in air at atmospheric pressure, averages about 3,000 per mm. of path. The ionization is thus confined to columns of very small cross-section, in which the density of the ionization is very high. The rate of recombination is, therefore, rapid, and it is difficult to obtain saturation.

The β-rays travel in a somewhat tortuous path, and are much less efficient in ionizing. A high speed β-particle produces only about 10 to 20 ions per mm. of path. Thus the ionization due to β-particles is more uniform and not so intense as that due to α-rays, and in general saturation is obtained easily.

---

* i.e. at 0° C. and 760 mm. of mercury.

CHAPTER III

METHODS OF MEASUREMENT

15. Electrical Method. The most generally useful method of examining the radiations from radioactive bodies depends on their property of ionizing a gas. As pointed out in § 9, the saturation current through an ionized gas is a direct measure of the rate of production of ions, and consequently of the intensity of the ionizing radiations.

The electric field necessary to produce saturation varies with the intensity of the ionization, and, therefore, with the activity of the preparation under examination. Under usual conditions a field of 100 volts per cm. is sufficient to give practical saturation.

The difficulty of obtaining saturation when the ionization is due to α-rays has been mentioned in § 14. It is found, however, that even when saturation is far from complete the currents observed bear nearly the same relation to each other as the true saturation currents. A field of 100 volts per cm. will give, for α-ray ionization, about 85 per cent. of the true saturation current, and this is sufficient for most comparative measurements.

As a general rule, the ionization currents are much too feeble for measurement by the galvanometer, and a more sensitive instrument must be used, some type of electrometer or electroscope. Many of the observations of radioactivity consist in measuring the change with time of the activity of a preparation or in comparing the radiations of two substances under the same conditions. For such observations, the electroscope is the simplest and most convenient instrument.

16. The α-Ray Electroscope. A convenient form of electroscope for the measurement of α-rays is shown in Fig. 8. The active material is placed on the plate *A*. The upper plate *B* is carried by the rod *C*, which is held by the sulphur stopper *S*. The rod *C* carries a gold-leaf *L*, and this insulated system can be charged by removing the cap *K*. The plate *A* and the case of the instrument are connected to earth. The side *D* of the lower case opens on a hinge to allow the active material to be placed in position.

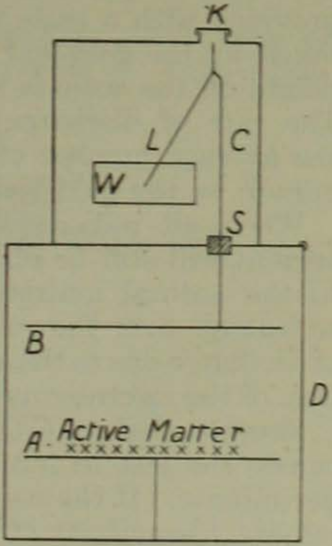

FIG. 8.—ELECTROSCOPE FOR MEASUREMENT OF α-RAYS

The lower half of the electroscope forms the ionization chamber (*cf.* Fig. 4), and the upper half forms the instrument which measures the current through the ionized air.

The gold-leaf system *BCL* is charged to a potential of from 300 to 400 volts, giving a deflection of about 40° to the leaf. This voltage is sufficient to give approximate saturation when the plates *A*, *B* are not more than 4 cm. apart. When the air between *A* and *B* is ionized the potential of *B* will decrease, and the gold-leaf will fall gradually. The current through the air is measured by the rate of loss of potential of the plate *B*, and this is proportional to the rate of movement of the gold-leaf. The movement of the gold-leaf is observed through the window *W* by a microscope, of magnification about 10-times, provided with a scale in the eyepiece. The time taken by the gold-leaf to pass between two fixed points on the scale is measured by a stop-watch. The rate of discharge is generally expressed as the average number of divisions passed over per minute by the gold-leaf.

When all radioactive material is removed a current will still be observed. This is due partly to the natural ionization of the air, and partly to leakage over the sulphur insulation. The rate of discharge due to these causes is called the natural leak of the electroscope, and should be very small.

Suppose that an active material on the plate *A* causes the leaf to fall at the rate of n_1 divisions per minute. If the natural leak is n divisions per minute, the activity of the material is proportional to $n_1 - n$. If a standard source of uranium oxide gives n_2 divisions per minute, then the activity of the material relative to the standard is—

$$(n_1 - n)/(n_2 - n).$$

It is often necessary to measure the activity of a substance at intervals over a long period of time. As the sensitiveness of the electroscope may change during this time, some method of standardizing the electroscope is necessary. This is done by the use of a standard source, consisting of a thin layer of uranium oxide of suitable area. The activity of uranium oxide is practically constant. The current due to the substance under observation is compared, as above, with that due to the uranium standard. The ratio of the two currents will be independent of any variation in sensitiveness of the electroscope.

17. β- and γ-Ray Electroscopes. The type of electroscope used for measuring β- and γ-rays

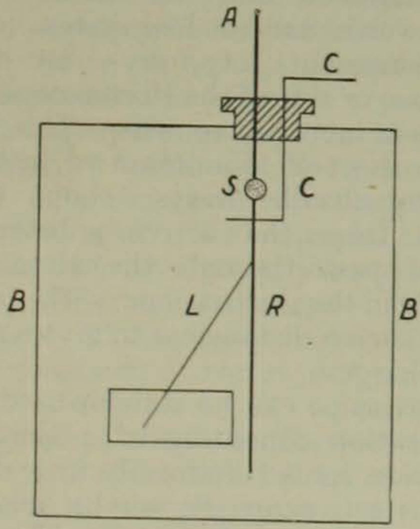

FIG. 9.—ELECTROSCOPE FOR MEASUREMENT OF β- AND γ-RAYS

is shown in Fig. 9. The gold-leaf system consists of a narrow gold-leaf *L* attached to a flat rod *R*. This is insulated inside a vessel *B* by a small sulphur bead *S* supported from the rod *A*, and can be charged by a light bent wire *CC* passing through an ebonite stopper. The wire *C* is charged by means of an ebonite rod or by connecting to a battery of about 300 volts. The charging wire *C* is then turned so that contact with the leaf system is broken, and *C* is connected to earth. The rod *A* and the vessel *B* are also connected to earth.

The rate of movement of the gold-leaf is observed by a microscope through windows in the vessel, and measurements are made as with the α-ray electroscope. In this case, the vessel *B* is the ionization chamber, and the electrodes are the walls of the vessel and the leaf system.

For measurements of β-rays, an opening is cut in the base or side of the electroscope according as to which is more convenient. This is covered with a thin sheet of aluminium of just sufficient thickness to absorb α-rays, about 0·006 cm. The β-rays from the active substance under examination pass through the aluminium and ionize the air in the electroscope. The preparation is placed at such a distance as to give a convenient rate of discharge.

The electroscope can be standardized by means of a preparation consisting of a thick layer of uranium oxide spread uniformly in a dish.

A γ-ray electroscope is usually made of lead with walls at least 3 mm. thick. The β-rays are completely absorbed in this thickness of lead, and the ionization in the electroscope is due entirely to γ-rays. The source of γ-rays is placed at a suitable distance to one side of the electroscope. The γ-radiation from a known quantity of radium in a sealed glass tube gives a convenient method of standardizing a γ-ray electroscope.

18. Luminosity and Photographic Action. It has already been mentioned that, in addition to producing ions in a gas, the radiations act upon a photographic plate and produce luminosity in many substances, e.g. barium platinocyanide, zinc sulphide, and willemite. These effects can be used as a means of examining the radiations.

The luminosity produced by the β- and γ-rays affords only an insensitive method of showing the presence of these radiations. On the other hand, the luminosity produced by the α-particles in zinc sulphide has given a direct and simple method of counting the α-particles, and has been of great value in α-ray investigation. This method is discussed in § 25.

The photographic method is also unsuitable for quantitative work, but has given a valuable means of detecting and recording the position of a pencil of rays. For example, the curvature of the path of the rays, when deflected by magnetic or electric fields, can be recorded on the photographic plate and the measurement of the curvature gives the constants of the rays.

19. Magnetic Deflection. The corpuscular radiations from radioactive substances are characterized by the mass m, the charge e, and the velocity v of the particles of which they consist. The separate determination of these quantities presents great experimental difficulties, but e/m, the ratio of the charge to the mass, and the velocity v can be deduced from measurements of the deflection of the particles in magnetic and electric fields.

It is well known that a conductor carrying a current in a magnetic field is acted on by a force at right angles, both to the direction of the current and to that of the magnetic force. Now the charged particles in motion correspond to a current element of magnitude ev. Consequently, if a stream OA (Fig. 10) of the particles be projected at right angles to the magnetic lines of force

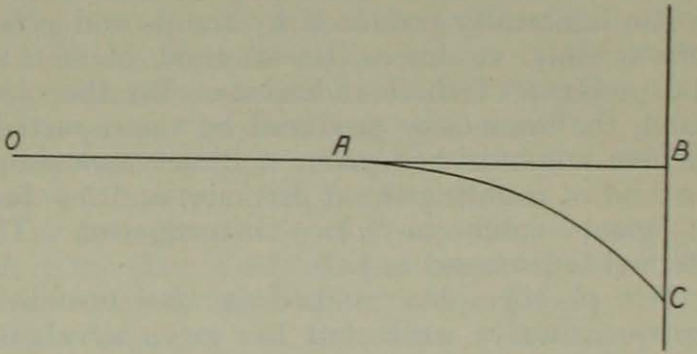

FIG. 10.—MAGNETIC DEFLECTION OF STREAM OF PARTICLES

(the direction of the latter being downwards through the paper), the stream of particles is bent upwards or downwards according as the charge e is positive or negative.

Since the force acting on each particle is at each instant at right angles to its direction of motion, the velocity of the particle remains unchanged. The path of the particle will be part of a circle, for the force acting on the particle is Hev, where H is the strength of the magnetic field, and if ρ is the radius of curvature of the path, we must have—

$$Hev = mv^2/\rho$$

$$\text{or } H\rho = mv/e.$$

Since v is constant, ρ is also constant, i.e. the particle travels in a circular orbit.

In Fig. 10, the pencil OA enters the magnetic field at A, and is bent from its original direction OAB along the circular path AC. The radius of the circle can be deduced from the deflection BC. A photographic plate placed at BC will record a mark at B for the direct pencil when no magnetic field is applied, and another at C on application of the field. The deflection BC can then be measured.

20. Electric Deflection. If the particles pass through an electric field, say, in the direction OAB between two parallel plates L, M (Fig. 11), they will be deflected towards L or M according as their charge is positive or negative. If the electric force X between the plates is uniform, the particles will have a constant acceleration a, given by $ma = Xe$, in a direction perpendicular to OAB. The particles thus move with uniform horizontal velocity with a uniform vertical acceleration. Their path will be similar to that of a stone projected horizontally and falling under gravity,

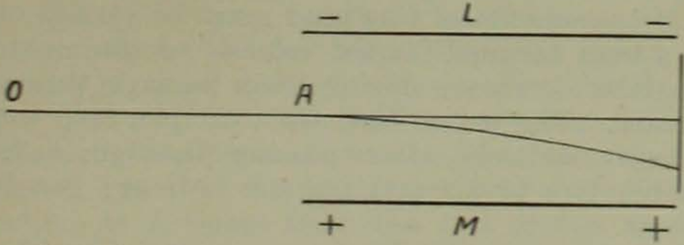

FIG. 11.—ELECTRIC DEFLECTION OF STREAM OF PARTICLES

i.e. a parabola of which OAB is a tangent at the vertex A.

If the length of the plates be l, the time taken by a particle to traverse the electric field is l/v. The distance BC passed over in this time under the constant acceleration is

$$\tfrac{1}{2}\frac{Xe}{m}\cdot\frac{l^2}{v^2}$$

or, putting $BC = d$, $mv^2/e = Xl^2/2d$.

Thus, measurements of the deflection in an electric field give the value of mv^2/e and, combining this result with the value of mv/e obtained from the deflection in a magnetic field, we get the ratio e/m and the velocity v of the particles.

Measurements of this kind must be carried out in a high vacuum, for the velocity of the moving particles decreases during their passage through matter. The α-particles, for example, lose their velocity entirely after passing through a few centimetres of air and become ordinary gaseous atoms.

CHAPTER IV

THE RADIATIONS. THE α-RAYS

21. Methods of Investigation. There are two general methods of investigating the radiations emitted by the radioelements. The first of these consists in observing whether the rays are deflected in magnetic and electric fields. The radiations consisting of charged particles will be deflected; the direction of the deflection decides whether the charge is positive or negative, and its amount gives information as to the velocity, and the ratio of the charge to the mass of the particles.

In this way it was found that the radiations consist of three distinct types, called the α-, β-, and γ-rays. The effect of a magnetic field in separating out the radiations is illustrated by Fig. 12. A pencil of the radiations emitted by some radium at *R* issues from the end of the narrow cylinder. The magnetic field is at right angles to the plane of the paper and is directed downwards.

The γ-rays continue without deflection. The β-rays are deflected to the right, showing that they are negatively charged particles. The amounts of the magnetic and electric deflections show that the β-rays are identical in type with the cathode-rays in a vacuum tube. The α-rays are deflected to the left, and both the magnetic and electric deflections are very small compared with the corresponding quantities for the β-rays. The α-rays are, therefore, positive particles of large mass.

In the figure the deviation of the α-rays is greatly exaggerated.

The second method of investigating the radiations consists in comparing their relative absorptions by solids and gases, using the electroscope as a means of measurement.

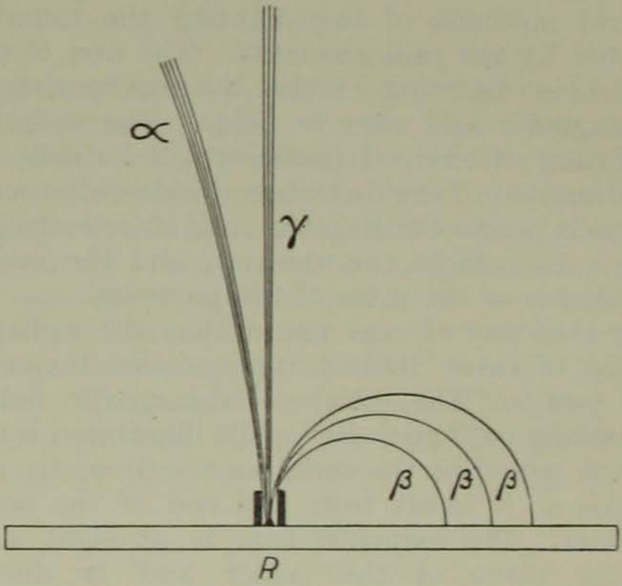

FIG. 12.—EFFECT OF MAGNETIC FIELD ON α-, β-, AND γ-RAYS

22. Penetrating Powers of the Radiations. It is found that the α-rays are the most easily absorbed by matter, and the γ-rays the least. The α-rays are completely absorbed in a few centimetres of air or by thin foils of matter. A sheet of aluminium 0·006 cm. thick or a sheet of ordinary writing paper is sufficient to absorb all the α-rays. When such a sheet is placed over an active preparation, any residual ionizing effect is due to β- and γ-rays. The β-rays vary greatly in penetrating power, but are practically all absorbed in 5 mm. of aluminium or 1 mm. of lead. The effect through screens of this thickness is due to γ-rays. The γ-radiation from 30 mg. of radium can be detected through 30 cm. of iron.

Roughly, we may say that the β-rays are about 100 times as penetrating as the α-rays, and the γ-rays 100 times as penetrating as the β-rays. On the other hand, the α-rays produce by far the greater part of the ionization around a radioactive source emitting α-, β-, and γ-rays, and the γ-rays least.

THE α-RAYS

23. Magnetic and Electric Deflections of α-Rays.

Measurements of the deflection of α-rays in magnetic and electric fields show that the α-particles emitted by a single radioactive product all have the same initial velocity. This velocity of expulsion of the α-particles is characteristic of the transformation giving rise to them. For example, the α-rays expelled during the transformation of radium emanation are emitted with a velocity of $1{\cdot}62 \times 10^9$ cm. per sec., and those of *RaC* are emitted with a velocity of $1{\cdot}92 \times 10^9$ cm. per sec.

On the other hand, the ratio of the charge to the mass of the α-particles is the same for all α-particles, whatever their origin. This suggests that all α-particles emitted by radioactive substances are identical, except as regards velocity, and consist of the same kind of matter.

The experimental value of e/m for the α-particle is 4,823 in electromagnetic units. Now the value of e/m for the hydrogen ion in electrolysis is 9,649 in the same units, and the hydrogen ion carries unit negative charge. If the α-particle carries unit positive charge its mass will, therefore, be twice that of the hydrogen atom ; if the α-particle carries two charges its mass will be four times that of the hydrogen atom, i.e. equal to the mass of the helium atom. The measurement of the charge of the α-particle was thus an important problem, and was attacked by Rutherford and Geiger, who measured the total charge carried by a known number of α-particles.

24. Counting of α-Particles. There are two direct methods of detecting a single α-particle, the electrical method and the scintillation method. The electrical method depends on the principle of ionization by collision, discussed in § 13.

The earliest form of α-ray counter, devised by Rutherford and Geiger, is shown in Fig. 13. It consisted of a cylinder A, carrying an insulated central wire B passing through ebonite plugs at the ends. The cylinder was connected to the negative pole of a battery of 1,500 volts, and the central electrode was connected to an electrometer. The voltage on the cylinder and the pressure of the gas in the cylinder were adjusted so that any ions produced in the gas were multiplied several thousand times by collision. The magnification was so great that the entrance of a single α-particle through the window O produced a measurable deflection of the electrometer.

A counter devised more recently by Geiger has the great advantage that the gas in the counter may be at atmospheric pressure. A sharp needle ends about 1 cm. from the opening O (Fig. 14), through which the α-particles enter. When the outer brass tube is charged positively to about 1,000 volts and the needle is connected to a string electrometer, the entrance of an α-particle causes a large deflection.

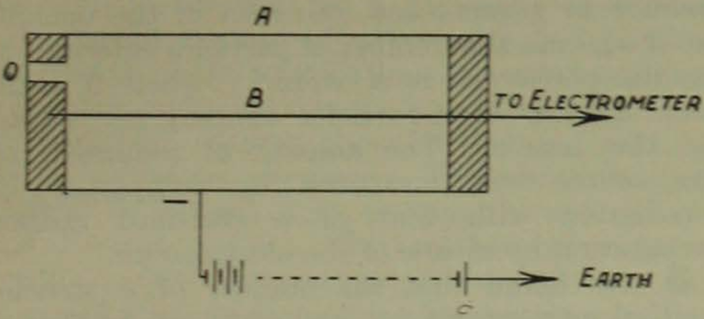

FIG. 13.—α-RAY COUNTER. (Rutherford and Geiger)

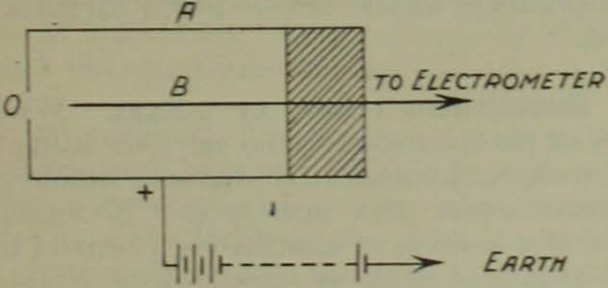

FIG. 14.—α- AND β-RAY COUNTER. (Geiger)

This counter is so sensitive that the entrance of a single β-particle gives a measurable deflection.

With the aid of the electrical counter Rutherford and Geiger determined the rate of emission of α-particles from a source of radium-C. The source was placed in an evacuated tube, at the end of which the counter was situated. If the distance from the source to the opening of the counter be r cms., and the area of the opening be A sq. cm., the number of particles entering the counter per second is $N/A/4\pi r^2$; where N is the total number of α-particles emitted per second by the source. The amount of radium-C on the source was measured by comparing its γ-radiation with that of a standard radium preparation by means of the electroscope.

It was found that the number of α-particles emitted per second by the product radium-C in radioactive equilibrium with 1 grm. of radium was $3{\cdot}4 \times 10^{10}$. The same number is emitted by 1 grm. of radium itself, and by each of the three α-ray products, radium emanation, radium-A and radium-C, in equilibrium with it. Consequently 1 grm. of radium in equilibrium with these products emits $13{\cdot}6 \times 10^{10}$ α-particles per second.

25. Scintillations caused by α-Rays. When a screen of phosphorescent zinc sulphide is exposed to the α-rays, a luminosity is produced which, when examined under the microscope, is found to consist of a number of scintillating points of light. These points of light, or scintillations, come and go with great rapidity. Rutherford and Geiger found, by comparing the observed number of scintillations with the number of α-particles falling on the screen as determined by the electrical method, that each scintillation corresponds to the impact of one α-particle on the zinc sulphide. On a uniform screen every α-particle produces a visible scintillation. We thus have an extremely simple method of counting α-particles.

The screen is made by dusting a thin layer of zinc sulphide crystals on a cover-slip moistened with a small amount of adhesive material. The observation of the scintillations is carried out in a dark room, and a microscope is used of magnification about 40, with an objective of large aperture and a low-power eyepiece. The screen is illuminated by a weak light, so that the eye can be kept focused on it. This method provides a powerful means of investigating α-ray phenomena.

Certain kinds of diamonds also exhibit scintillations, but they are not so brilliant as those of zinc sulphide.

26. Charge of the α-Particle. Since the number of α-particles emitted from a source can be counted directly, the charge of a single α-particle can be found by measuring the charge carried by a known number of α-particles. This was done by Rutherford and Geiger, using radium-C as the source of α-rays.

The principle of the method is as follows. The α-rays from a source which hit a plate are stopped in the plate and give up their charge to it. The gain of charge by the plate is measured by an electrometer. The amount of the source is measured by its γ-radiation in terms of radium, and the number of α-particles hitting the plate is deduced from the previous counting experiments. On account of the ionization produced by the rays, the experiment must be carried out in an evacuated chamber, and various precautions must be taken.

The value of the positive charge carried by the α-particle was found to be $9{\cdot}3 \times 10^{-10}$ electrostatic units.

A similar determination was made by Regener, who measured the charge carried by a known number of α-rays emitted from a polonium (radium-F) source. The rate of emission of α-particles from the source was found by counting the scintillations produced on a small slip of diamond. Regener found the charge of the α-particle to be $9{\cdot}6 \times 10^{-10}$ electrostatic units, in good agreement with the above value.

Comparing this charge with the value of $4{\cdot}77 \times 10^{-10}$ electrostatic units found by Millikan for the fundamental unit of charge, it is seen that the α-particle must carry two unit positive charges.

27. Nature of the α-Particle. Combining this with the values of e/m of the α-particle and of the hydrogen ion (§ 23), it appears that the mass of the α-particle is four times that of the hydrogen atom. The obvious conclusion is that the α-particle is an atom of helium associated in some way with two positive charges.

This was confirmed by direct experiment by Rutherford and Royds, who collected α-particles in an evacuated space, and obtained the spectrum of helium on passing a discharge. The essential part of the apparatus is shown in Fig. 15. A large quantity of radium emanation was compressed into the tube *A*. The walls of this tube were less than 0·01 mm. thick, so that the α-particles emitted by the emanation and its products escaped from the tube. The tube *A* was surrounded by the tube *T*, to which was attached a spectrum tube *V*. The tube *T* was completely exhausted at the beginning of the experiment. The α-particles collected in T, if forming a gas, could be compressed into the spectrum tube by raising the mercury Hg, and the nature of the gas could then be determined spectroscopically.

Two days after the emanation had been introduced into A, the spectrum showed the yellow line of helium, and after 6 days the whole helium spectrum was obtained. The helium had not diffused through the thin walls of the tube A, for when the tube was filled with helium, no trace of helium was observed in the spectrum tube, even after several days. The helium observed had, therefore, originated from the α-particles.

In other experiments the α-particles were collected by firing them into a cylinder of lead placed round a tube similar to A. On melting the lead in a closed vessel the helium was collected and detected by its spectrum.

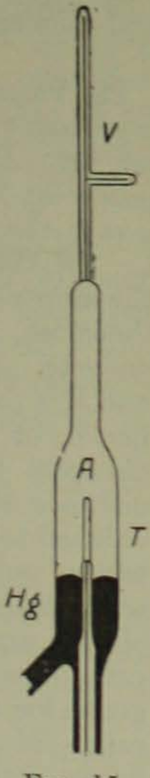

Fig. 15.
Helium from α-Particles.
(Rutherford and Royds)

These experiments showed definitely that the α-particle, when its charge is neutralized, becomes an ordinary helium atom. Now, on the nuclear theory, the helium atom consists of a nucleus of mass 4 and charge $+ 2e$, attended by two negative electrons. It seems clear, therefore, that the α-particle must be the helium nucleus in rapid motion. When, owing to its passage through matter, the velocity of the α-particle is reduced to the order of molecular velocities, the α-particle picks up two electrons and becomes an ordinary helium atom.

28. Passage of α-Rays through Matter. The α-particles diminish in velocity in passing through matter. If a uniform screen of matter be interposed in the path of a homogeneous pencil of α-rays, the pencil remains very nearly homogeneous, i.e. all the α-particles have suffered practically the same reduction in velocity. It is to be expected therefore, that α-particles of the same initial velocity will travel nearly the same distance; and it is found that the ionization due to a parallel pencil of α-rays from a simple product ends abruptly at a certain distance in air. At this distance the velocity of the α-particles has been reduced to such a value that the particles no longer ionize, act on a photographic plate, or produce scintillations. This distance is called the range of the α-particle in air. The range is inversely proportional to the density of the air, and is usually given for air at 760 mm. pressure and 15°C. The range of the α-particles emitted by radium-*C* in air at this temperature and pressure is 7 cm.

Suppose that a uniform sheet of aluminium, placed over a source of radium-*C*, reduces the range to 5 cm. Then the sheet is said to have a "stopping power" equivalent to 2 cm. of air. From the weight per unit area of the sheet the number of atoms of aluminium through which the α-particle has passed can be found, and the stopping power of the aluminium atom compared with that of the average air atom. By measuring the stopping powers of known thicknesses of different materials, the stopping powers of different atoms can be compared. These measurements have shown that the stopping power of an atom is roughly proportional to the square root of its atomic weight. Thus the stopping power of the oxygen atom is four times that of the hydrogen atom, or the range of an α-particle in oxygen is one-quarter of its range in hydrogen.

The decrease of velocity of the α-particles in passing through matter was measured by observing the deflection of the rays in a magnetic field when different screens of known stopping power were placed over the source. It was found that the velocity V of an α-particle and its range R are connected by the simple relation

$$V^3 = aR,$$

where a is a constant.

The velocity of the α-particle decreases in its passage through matter in consequence of the expenditure of its energy in ionizing the atoms through which it passes. If the production of ions depends upon the velocity of the α-particle, the ionization will vary greatly along the path of the α-particle.

29. Ionization Curve. The rate of production of ions along the path of the α-particle was investigated by means of an apparatus similar to that shown in Fig. 16. A narrow cone of α-rays from the source R passes into the shallow ionization chamber AB, the face A of which is a wire gauze. The current between A and B is measured by an electroscope or electrometer. By varying the distance of AB from the source, the ionization produced by the α-particles can be measured at different points of their path in air.

If a thin layer of a simple radioactive product is used, the rate of production of ions increases as the distance from the source increases, passes through a maximum, and falls rapidly to zero.

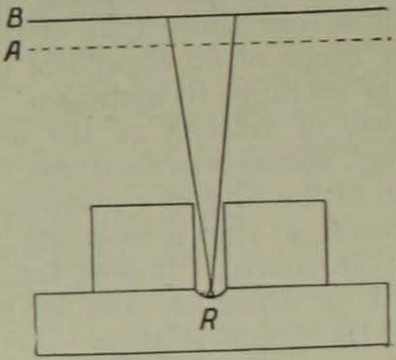

Fig. 16.—Investigation of Rate of Production of Ions along the path of α-Particles

Fig. 17 shows an ionization curve taken in this way for the α-particles of radium-C, the ordinates representing the current observed and the abscissal the distance in air from the source. This ionization curve is typical for the α-rays emitted by all products. For example, the curve due to the α-rays emitted by polonium, the range of which is 3·8 cm., is the same as the part of the curve for radium-C between 3·2 and 7 cm. from the source.

This curve represents the variation of ionization along the path of a pencil of α-particles. If the pencil remained perfectly homogeneous to the end of the range, the curve would also represent the variation of ionization along the path of a single α-particle, but this is not the case. It has been found by the scintillation method that, however narrow the pencil of rays, the number of α-particles in the pencil begins to diminish about 1 cm. from the end of the range, and falls rapidly to zero (Fig. 18). These variations in number and velocity of the α-particles at the end of the range are ascribed to scattering of the particles by close atomic encounters. The distance at which ionization ceases marks the maximum range of the α-particles, while the average range is about 4mm. less.

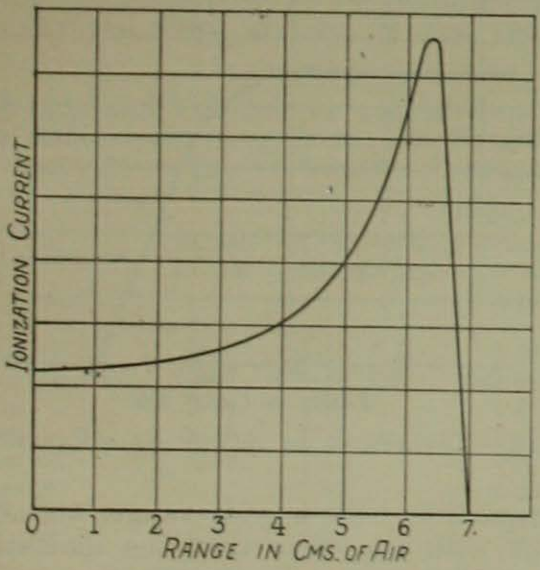

FIG. 17.—VARIATION OF IONIZATION ALONG PATH OF A PENCIL OF α-PARTICLES

The observed ionization curve of Fig. 17 is thus built up of a large number of similar curves grouped about the curve corresponding to average range.

It appears probable that the rate of production of ions is inversely proportional to the velocity of the α-particle over a wide range, and this is consistent with the view that the ionization is proportional to the energy absorbed.

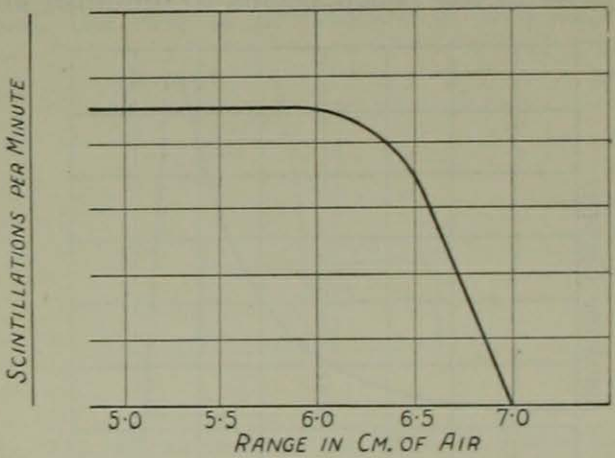

Fig. 18.—Variations in Range of α-Particles

30. Range of α-Particles. The maximum range of the α-particles emitted by a radioactive product is a characteristic constant of the product. The value of the range depends on the nature of the absorbing gas, and for a given gas varies inversely as its density. It is usually given in terms of air at 760 mm. pressure and 15°C. Measurements of the range of the α-particles of a product can be made by the electrical and scintillation methods described in the previous section. Owing to the difficulty of observing the weak scintillations at the end of the range, the scintillation method gives a value of the range 1 or 2 mm. less than that found by the electrical method.

The ranges of the α-rays emitted by the radioactive substances are given in Table I. The ranges given are for air at 760 mm. pressure and 15°C. In the third column is the velocity V

TABLE I

RANGE AND VELOCITY OF α-RAYS EMITTED BY RADIOACTIVE SUBSTANCES, AND NUMBER OF IONS PRODUCED BY SINGLE α-PARTICLES

Radio-element.	Range in cm.	Velocity in cm. per sec.	No. of Ions produced by single α-particle.
Uranium-I . .	2·67	$1{\cdot}40 \times 10^9$	$1{\cdot}25 \times 10^5$
Uranium-II . .	3·07	1·46	1·37
Ionium . . .	3·19	1·48	1·41
Radium . . .	3·39	1·51	1·46
Emanation . .	4·12	1·61	1·67
Radium-*A* . .	4·72	1·69	1·83
Radium-*C*. . .	6·97	1·922	2·37
Radium-*F*. . .	3·92	1·59	1·62
Protoactinium .	3·67	1·55	1·55
Radioactinium .	4·68	1·68	1·82
Actinium-*X* . .	4·37	1·64	1·74
Emanation . .	5·79	1·81	2·09
Actinium-*A* . .	6·58	1·89	2·28
Actinium-*C* . .	5·51	1·78	2·02
Thorium . . .	2·90	1·44	1·32
Radiothorium .	4·02	1·60	1·64
Thorium-*X* . .	4·35	1·64	1·74
Emanation . .	5·06	1·73	1·92
Thorium-*A* . .	5·68	1·80	2·07
Thorium-*C* . .	4·79	1·70	1·84
Thorium-*C′* . .	8·62	2·06	2·74

deduced from the range by the formula $V^3 = aR$ (§ 28), assuming that the velocity of the α-particles emitted by radium-C is $1{\cdot}922 \times 10^9$ cm. per sec. The fourth column gives the total number of ions produced by a single α-particle of the corresponding range. This is a measure of the energy of the α-particle.

31. Scattering of α-Particles. The α-particle in general travels through matter in a straight line, its energy of motion being so great that intense forces are necessary to deflect it. The path of the α-particle lies on the whole through the electronic distributions of the atoms, and thus the average particle is subjected only to the small forces exerted by the electrons. Occasionally, however, an α-particle will pass close to the nucleus of an atom. Owing to its large positive charge the nucleus of a heavy atom is surrounded by an intense electric field, and when the α-particle enters this field it is deflected from its straight path. The nearer the α-particle passes to the nucleus, the greater will be its deflection.

Assuming that the electric force around the nucleus varies according to the usual inverse square law, Sir Ernest Rutherford has shown that the α-particle will describe a hyperbolic orbit round the nucleus, and the fraction of α-particles deflected through any angle can be calculated in terms of the known constants of the α-particles and the charge on the nucleus. By comparing the observed scattering of α-particles with this theoretical distribution the nuclear theory of atomic structure can be submitted to a direct experimental test.

The results are in complete agreement with theory. No other law of force but that of the inverse square is consistent with the observations, and the value of the nuclear charge deduced from the scattering of α-particles is the same as that indicated by evidence from other sources.

It follows that the theory of atomic structure outlined in § 5 stands on a firm experimental basis, and may safely be used in the interpretation of radioactive phenomena.

CHAPTER V

THE RADIATIONS (*continued*). THE β- AND γ-RAYS

The β-Rays

32. Magnetic and Electric Deflection of β-Rays. Early observations showed that the β-rays emitted by radioactive bodies were deflected in magnetic and electric fields in the same direction and to about the same extent as the cathode rays of a vacuum tube. They are, in fact, identical in nature with the cathode rays, i.e. they are negative electrons moving with high velocity.

The β-rays emitted by a simple radioactive product are not homogeneous, but have widely different velocities. Accurate measurement of the magnetic and electric deflections shows that the value of e/m for the β-particle is not constant, but decreases with increasing velocity of the particle. Since the β-particle carries unit charge, this must mean that its mass increases with the velocity. This is to be expected, for, on the relativity theory, the mass of a moving body is a function of its velocity. If m_o be the mass of the particle at rest, its mass when its velocity is a fraction β of the velocity of light is given by—

$$m = m_o \, (1 - \beta^2)^{-\frac{1}{2}}$$

For ordinary velocities the mass is constant for all practical purposes but, as the velocity approaches the velocity of light, the mass increases rapidly.

Thus, for $\beta = 0{\cdot}5$, a velocity of $1{\cdot}5 \times 10^{10}$ cm. per sec., $m = 1{\cdot}15 m_o$; for $\beta = 0{\cdot}9$, $m = 2{\cdot}3\ m_o$; and for $\beta = 0{\cdot}99$, $m = 7\ m_o$.

The observed variation of e/m with the velocity of the β-particle agrees with the predictions of the relativity theory.

For low velocities, when $m = m_o$, the value of e/m is $1{\cdot}77 \times 10^7$ in electromagnetic units. Comparing this with e/m for the hydrogen ion, which also carries unit charge, we find that the mass of the β-particle is only $\frac{1}{1800}$ of the mass of the hydrogen atom.

It is generally assumed that the mass of the β-particle is wholly electromagnetic in origin, that is due to the concentration of the charge on a small volume. There is no definite evidence for or against this assumption, and its simplicity has much to commend it. On this view, the radius of the β-particle is about 2×10^{-13} cm.

33. Velocity Distribution of β-Rays. Information as to the distribution with velocity of the β-particles from an active source can be obtained from the magnetic deflection alone. A convenient method of investigating their distribution is shown in Fig. 19. The β-rays emitted by the source R pass through the slit S carried by the lead block L, and describe circular orbits in a magnetic field perpendicular to the plane of the paper. A photographic plate placed on the lead block is acted upon where the β-rays fall on it. The apparatus is enclosed in an evacuated brass box.

As will be seen from the figure, a cone of rays of the same velocity is brought to a focus on the photographic plate. The rays of lower velocity are focused nearer the slit. Thus if the source *R* emitted a homogeneous beam of β-rays a sharp band would be obtained on the photographic plate, and the position of the band would give the velocity of the rays.

When the β-rays emitted by a thin layer of active matter, say, a deposit of radium-*B* and -*C*, are examined by this method it is found that numerous sharp bands are obtained on the photographic plate, corresponding to sets of homogeneous β-rays with different velocities. These groups are characteristic of the active source. Besides the groups or "line spectrum" of the β-rays there is a background or "continuous spectrum."

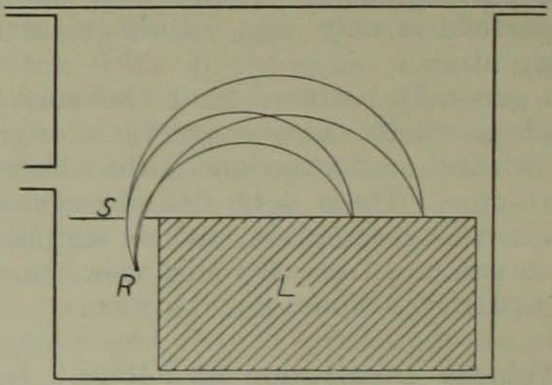

FIG. 19.—MAGNETIC DEFLECTION OF β-RAYS

When the relative intensities of the lines and the continuous spectrum are observed by an electroscope or by a β-ray counter, it is seen that only four of the groups found for radium-*B* and -*C* stand out clearly from the continuous spectrum.

The other lines are only slightly more intense than the background. The emission of β-rays is thus a very complex phenomenon, in striking contrast to the emission of α-rays. For example, the β-rays emitted by radium-*B* and -*C* together vary in velocity from about 0·3 to 0·99 of the velocity of light and consist of about forty distinct sets superimposed upon a continuous background. The total number of β-particles emitted corresponds approximately to one for each atomic transformation.

The velocities of the chief groups in the β radiations of some of the products are given in Table II.

TABLE II

VELOCITIES OF CHIEF GROUPS IN β-RADIATIONS

Radio-element.	Velocity of Groups (velocity of light = 1).
Uranium-*X*	continuous spectrum
Radium-*B*	·36 ·41 ·63 ·70 ·75
Radium-*C*	·78 ·87 ·89 ·95 ·96 ·97
Radium-*E*	continuous spectrum ·7 to ·94
Mesothorium-2 . . .	·37 ·39 ·43 ·50 ·57 ·60 ·66
Thorium-*C* + *D* . .	·29 ·36 ·72—·95 (band)

34. Passage of β-Rays through Matter. The phenomena accompanying the passage of β-particles through matter are very complicated, and no final conclusions have been reached. This is due to some extent to the difficulty of obtaining conveniently a strong pencil of homogeneous β-rays. As we have seen, the β-rays are expelled from a simple product with a wide range of velocities;

to obtain a homogeneous beam it is necessary to separate out the rays by a magnetic field. A homogeneous pencil of β-rays, after passing through some thickness of matter, becomes heterogeneous. Some of the particles lose their velocity gradually by a long succession of atomic encounters, while others may suffer a sudden large loss from a single encounter. Although the velocity of the β-particle is on the average about 10 times that of the α-particle, its mass is so small that its momentum and energy are much less than the corresponding quantities for the α-particle. On this account, the β-particle is much more readily deflected in its encounters with the atoms in its path. This scattering is so marked that a considerable fraction of the β-rays incident on a metal foil emerge again on the side of incidence. Thus practically no β-particle has a straight path in matter. It appears probable that the β-particles, like the α-particles, have a definite range in matter, but this range must be taken to apply to the whole of its tortuous path.

Thus the passage of β-rays through matter depends on a number of factors, and the laws governing these are not known accurately.

35. Absorption of β-Rays. It is often convenient to distinguish between the β-rays of different products by their absorption in matter as measured by an electroscope. This is carried out in the following way. The source of β-rays is placed at a convenient distance below the opening of a β-ray electroscope. The ionization current in the electroscope is measured for different thicknesses of matter interposed between the electroscope and the source. When radium-E is used as the source of radiation, the current falls off with the thickness of matter according to an exponential law; i.e. I, the current for a thickness d cm. of absorbing material, is given by—

$$I = I_0 e^{-\mu d}$$

where I_0 is the current without absorbing screens, and μ is the coefficient of absorption of the material. If the logarithms of the currents are taken as ordinates, and the thickness of matter passed through as abscissae, the curve of absorption is a straight line. Such logarithmic curves, showing the absorption in aluminium for the β rays from uranium-X_2 and from radium-E are given in Fig. 20.

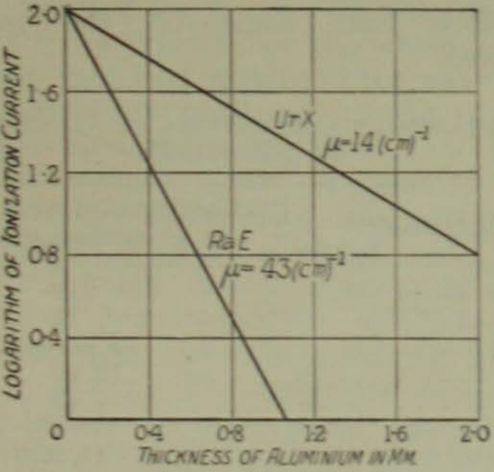

FIG. 20.—LOGARITHMIC CURVE OF ABSORPTION (β-RAYS)

The value of the absorption coefficient depends to some extent upon the experimental arrangement. In order to avoid initial disturbances due to scattering of the β-rays, the absorbing screens should be placed against the base of the electroscope.

For many of the products the absorption curve is approximately exponential. For others it is necessary to assume that the curve consists of two or three parts, each of which is exponential with a different coefficient.* Table III gives the absorption coefficients in aluminium of the β-radiations from some of the radioactive substances.

TABLE III

ABSORPTION COEFFICIENTS IN ALUMINIUM OF β-RADIATIONS

Radioelement.	Coefficient of Absorption in Aluminium μ (cm)$^{-1}$
Uranium-X_1 . . .	510
Uranium-X_2 . . .	14
Radium-B	13, 80, 890
Radium-C	13, 50
Radium-E	43
Mesothorium-2 . . .	20–38
Thorium-($C + D$) . .	14, 22

Comparison of the absorption in different substances shows that the absorption coefficient is roughly proportional to the density of the absorbing material.

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* In the case of radium-B, for example, the intensity of the β-rays measured through a thickness of d cm. of aluminium is—

$$I = I_1e^{-890d} + I_2e^{-80d} + I_3e^{-13d}$$

This means that radium-B emits β-rays of low velocity corresponding to the absorption coefficient 890, rays of medium velocity ($\mu = 80$), and rays of high velocity ($\mu = 13$).

The γ-Rays

36. Nature of the γ-Rays. The γ-rays are not deflected in magnetic and electric fields, and are far more penetrating than the α- and β-rays. On the average, the γ-rays are only slightly absorbed by a thickness of matter which completely stops the β-radiations. They are analogous in nature to the *X*-rays, consisting of electromagnetic impulses. Their properties are very similar to those of the *X*-rays, the chief difference being that the γ-rays are, on the whole, far more penetrating, that is of much shorter wavelength.

Since *X*-rays are produced by the impact of cathode particles on the anticathode, it is to be expected that when β-rays impinge on matter a γ-radiation will be excited; this production of γ-rays by β-rays has been observed. The *X*-rays, in passing through matter, liberate a type of β-radiation of low velocity; the γ-rays also liberate β-particles, but of high velocity and high penetrating power. The ionization produced in a gas by γ-rays is due to the β-rays liberated from the molecules. The *X*- and γ-rays thus ionize indirectly.

A direct proof of the electromagnetic nature of the γ-rays was obtained by the method which had proved so successful in the investigation of *X*-rays, by examining the diffraction of the rays at the surface of a crystal. Examination of the γ-rays of radium-*B*, for example, showed the presence of several lines of wavelength around 10^{-8} cm.

This method is not of general application as a means of examining the γ-radiations from radioactive substances. It depends on the scattering of the radiation by the atoms of the crystal, and this is very small for the penetrating γ-rays; and, secondly, it requires the use of more intense sources than are usually available. A more convenient method of examining the γ-rays is by their absorption in matter. It is known that homogeneous X-rays, i.e. X-rays of one wave-length, are absorbed in matter according to an exponential law, and it is to be expected that the same law will hold for γ-rays. Consequently, if a beam of γ-rays is absorbed according to an exponential law, we may conclude that the radiation is approximately homogeneous.

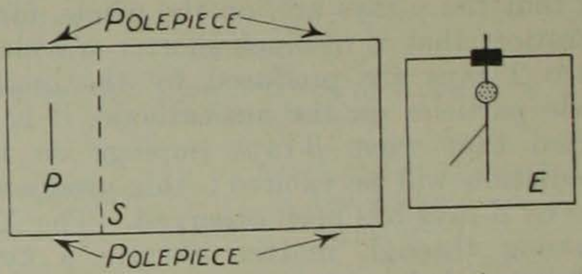

FIG. 21.—APPARATUS FOR EXAMINING ABSORPTION OF γ-RADIATIONS

37. Absorption of γ-Rays. The absorption of the γ-radiations from various products has been examined by means of the apparatus shown diagrammatically in Fig. 21. The source was placed at P between the polepieces of a strong electromagnet. The magnetic field deflected the β-rays emitted by the source and those produced by the γ-rays in the faces of the polepieces away from the electroscope E, which measured the γ-radiations. The ionization current in the electro-scope was measured for different thicknesses of aluminium placed at S.

Examined in this way, it was found that the γ-radiation of a product could be separated into one or more groups, each of which was absorbed according to an exponential law. For example, the ionization current observed for the γ-rays of radium-C through a thickness d cm., of aluminium is given by—

$$I = I_0 e^{-\mu d}$$

where I_0 is the current with no aluminium and $\mu = 0{\cdot}115$ (cm)$^{-1}$. For the radiation of radium-E it is found that—

$$I = I_0' e^{-\mu_1 d} + I'' e^{-\mu_2 d}$$

where $\mu_1 = 45$(cm.)$^{-1}$ and $u_2 = 0{\cdot}99$ (cm.)$^{-1}$

It is concluded, therefore, that radium-C emits a nearly homogeneous radiation, whilst radium-E emits two types of radiations, each of which is approximately homogeneous.

Some of the results obtained for the γ-radiations of the radioelements are given in Table IV.

TABLE IV

ABSORPTION COEFFICIENTS IN ALUMINIUM OF γ-RADIATIONS

Radioelement.	Absorption Coefficient in Aluminium μ(cm)$^{-1}$		
Radium-B	230	40	0·51
Radium-C			0·115
Radium-D		45	0·99
Radium-E		45	0·99
Actinium-B . . .	120	31	0·45
Mesothorium-2. . .		26	0·116
Thorium-B	160	32	0·36
Thorium-D . . .			0·096

For different materials the absorption coefficient μ is roughly proportional to the density D, i.e. μ/D is roughly constant.

38. Origin of the γ-Rays. The emission of β-rays by a radioactive substance is always accompanied by the emission of γ-rays. Since we know that cathode rays give rise to X-rays, and that β-rays in passing through matter give rise to γ-rays, it is reasonable to suppose that the γ-rays emitted by a radioactive product are produced by the β-rays in their escape from the atom. The examination of the γ-radiations of the various products has shown that they differ greatly from product to product both in amount and in penetrating power or wavelength. This is taken to indicate that the production of γ-rays depends upon peculiarities accompanying the passage of the β-rays through the atom. It is supposed that the β-particle, in passing through the electronic system around the nucleus from which it is emitted, suffers losses of energy which depend upon the path of the β-particle and the way in which these electrons are arranged. If the β-particle passes through regions where it is subjected to irregularly varying forces, only a weak γ-radiation is produced. The β-particle may, however, cross the atom in certain critical paths and disturb and set into vibration a ring of electrons, suffering itself a marked loss of energy. This energy reappears as γ-radiation emitted by the electron ring, of definite wavelength characteristic of the atom. The γ-rays may in turn eject from the atom β-particles of definite energy; these constitute the homogeneous groups of the β-ray spectrum

(§ 33). It has been possible on these lines to account for nearly all the groups in the β-ray spectrum of radium-B.

It has been found that α-ray products also emit a γ-radiation, though of small amount and low penetrating power. This is in accordance with the above explanation of the emission of γ-rays.

CHAPTER VI

RADIOACTIVE CHANGES

39. The Law of Transformation. In Chapter I it was stated that the phenomena of radioactivity are explained on the hypothesis that the atoms of a radioactive substance are unstable and break up with the formation of a new atom and the emission of one α- or one β-particle per atom. The number of α- or β-particles emitted per second from a simple product is, therefore, equal to the number of atoms of that product which disintegrate per second. Instead of counting the α- or β-particles emitted, it is simpler to observe the ionization current produced by them in an electroscope; for the saturation current is a measure of the number of ions produced in the electroscope, and this, under constant conditions of experiment, is proportional to the number of particles entering the electroscope. The ionization current produced in an electroscope by an active substance is then a measure of the rate of transformation of its atoms.

Now experiment shows that the activity of a simple product, measured under constant conditions, decreases with time according to an exponential law. For example, if a preparation of uranium-X be placed under a β-ray electroscope and its activity be measured from day to day, the curve of decay is as shown in Fig. 22. The activity of uranium-X decays to half value in 24 days, to 25 per cent. in 48 days, and so on.

Hence the number of atoms of a simple product which change in unit time diminishes according to an exponential law with the time. If n_0 is the number of atoms breaking up per second at time $t = o$, the corresponding number after an interval t is—

$$n_t = n_0 e^{-\lambda t}$$

where λ is a constant.

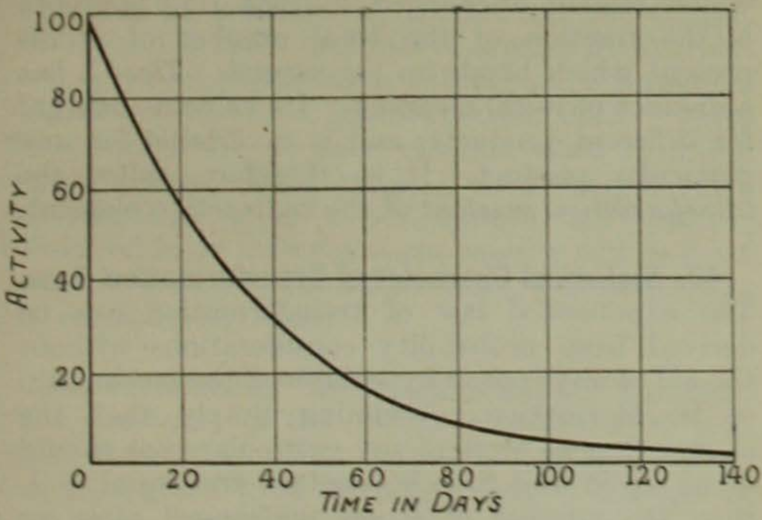

FIG. 22.—EXPONENTIAL CURVE OF DECAY: URANIUM-X

The number N_t of atoms which are unchanged after an interval t is equal to the number which change between t and an infinite interval of time, that is,—

$$N_t = \int_t^\infty n_0 e^{-\lambda t} \, dt$$

$$= n_0 e^{-\lambda t} \quad = n_t/\lambda$$

and the number of atoms present at time $t = o$ is $N_o = n_o / \lambda$. Thus— $N_t = N_o e^{-\lambda t}$ or the number of atoms of a radioactive substance decreases, according to an exponential law, with the time. This is the *law of transformation*, which governs all known radioactive changes.

Since $n_t = \lambda N_t$, the activity of a product at any time is proportional to the number of atoms which remain unchanged at that time; and λ is the fraction of the total number of atoms present which break up per second. Thus λ has a distinct physical meaning. Its value is different for different products, and is invariable for any particular product. It is, therefore, called the *transformation constant* of the radioactive element.

40. Statistical Character of Transformation Law. The exponential law of transformation can be derived from probability considerations without the aid of any special hypothesis of the mechanism of transformation. Assuming simply that the chance that an atom of any particular type should break up in unit time is constant and equal to λ, then the number of atoms unchanged after an interval t is—

$$N_t = N_o e^{-\lambda t}$$

where N_o is the number present initially.

Comparing this with the law of transformation we see that the transformation constant λ represents the chance of an atom breaking up in unit time. The law of transformation is thus a statistical law, and λ is the *average* fraction of atoms which break up in unit time. The number breaking up in any unit interval of time is subject to fluctuations round this average value, and the magnitude of these fluctuations can be calculated from the laws of chance. Since each α-particle corresponds to the transformation of one atom, we can follow the fluctuations in the number of atoms breaking up in a specified interval of time by a direct method. If the transformation of an atom is subject to the laws of chance the α-particles will be emitted at random both in time and space. This was investigated by Rutherford and Geiger, who found that the emission of α-particles followed a simple probability law, confirming the statistical character of the transformation law. These fluctuations are at once obvious when counting scintillations. For example, if the average number of scintillations is 4 per minute, the number observed in an interval of one minute will be most often 3, 4, and 5, but sometimes 0 and sometimes 10 or more may occur.

41. Invariability of Transformation Constant. The constancy of the law of transformation with time shows that the chance of any atom breaking up in a given time is independent of the age of the atom. It is therefore not possible to suppose that each atom immediately after formation begins to lose energy by radiation, and that its disintegration is the result of this loss of energy; for on this view the rate of decay would increase with the age of the atom. It appears rather that the transformation depends on some chance occurrence taking place in the atomic nucleus.

42. Average Life. Half-value Period. The law of transformation shows that an atom may exist unchanged for any time from zero to infinity. The "average life" of an atom is frequently used to express the rate of transformation of a product, and can easily be calculated. The number of atoms which break up in the interval dt after a time t is $\lambda N_t\, dt$ or $\lambda N_0 e^{-\lambda t}\, dt$. This is, therefore, the number of atoms which have a life t. Hence, the average life of the whole number N is

$$\int_0^\infty \lambda t e^{-\lambda t}\, dt \text{ or } 1/\lambda$$

Thus the reciprocal of the transformation constant gives the average life of the atoms of a product.

The rate of transformation of a product is given most conveniently by the time in which its activity decays to half-value. Putting $N_t = \frac{1}{2} N$ in the transformation equation, we get $\frac{1}{2} = e^{-\lambda T}$; where T is the half-value period, i.e. the time in which the activity falls to half-value. Thence, $T = 1/\lambda \; log_e 2 = 0{\cdot}693/\lambda$.

43. Successive Changes. As a general rule, a radioactive preparation consists not of a simple product but of a succession of products. Since each product transforms according to an exponential law, the number of atoms of any product in the series can be calculated.

Suppose the parent substance A of the series changes into B, B into C, etc. Each atom of A gives rise to one of B, each atom of B to one of C, etc. Then, if the number of atoms of $A . B$, C, . . . present initially be known, the numbers present after an interval of time t can be calculated in terms of the transformation constants.

Two simple cases only are here considered—

(*a*) The growth of B when produced by A at a constant rate, i.e. when the rate of transformation of A is very small.

(*b*) The growth of B when A is decaying rapidly.

44. Growth of Product by Slow Transformation of Parent Substance. (*Case* (*a*), § 43.) If the rate of transformation of the parent substance A is so small that the number of atoms of A may be regarded as constant during the interval under consideration, the number of atoms of A breaking up per second is constant and equal to p, say. This is, therefore, the number of atoms of B produced per second. No atoms of B are present initially. Let the number of atoms of B present after an interval t be Q. Then the number breaking up per second is λQ where λ is the transformation constant of B. The rate of increase of the atoms of B is—

$$\frac{dQ}{dt}=p-\lambda Q.$$

Integrating with the condition that $Q = o$ when $t = o$

$$Q = Q_m \left(1-e^{-\lambda t}\right), \text{ where } Q_m = p/\lambda.$$

The number of atoms of B thus approaches a limiting value Q_m, and the rise in the number is complementary to the decay which the substance undergoes when separated from its parent A. The limiting value is reached when the number of atoms of B breaking up per second is equal to the number supplied by the disintegration of A. A and B are then said to be in radioactive equilibrium.

An example of this case is shown in Fig. 23, which gives the rise of uranium-X from its parent uranium. The decay curve is added for comparison.

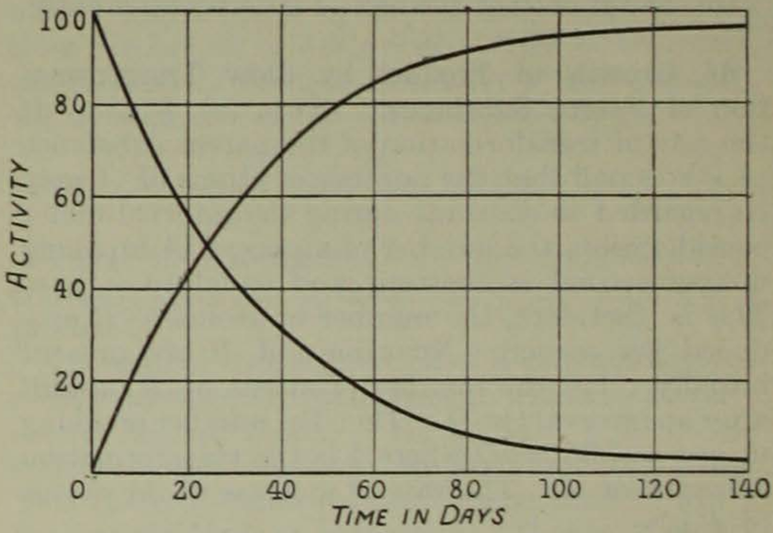

FIG. 23.—RISE AND DECAY OF URANIUM-X

45. Growth of Product by Rapid Decay of Parent Substance. (*Case* (*b*), § 43.) In this case the decay of the parent substance during the time of observation is not negligible. Let λ_1, λ_2 be the transformation constants, and P,Q the number of atoms present at time t for the substances A, B respectively. Then the number of atoms of B produced per second at time t is $\lambda_1 P$ and the number lost by disintegration is $\lambda_2 Q$.

Hence $$\frac{dQ}{dt} = \lambda_1 P - \lambda_2 Q$$

and $P = P_o e^{-\lambda_1 t}$, where P_o is the number of atoms of A present initially.

Since $Q = o$ when $t = o$.

$$Q = \frac{\lambda_1 P_o}{\lambda_2 - \lambda_1,} (e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

The number of atoms of *B* rises to a maximum and then decreases. After some time one of the exponential terms may become small compared with the other and the amount of *Q* then decays exponentially with the smaller transformation constant.

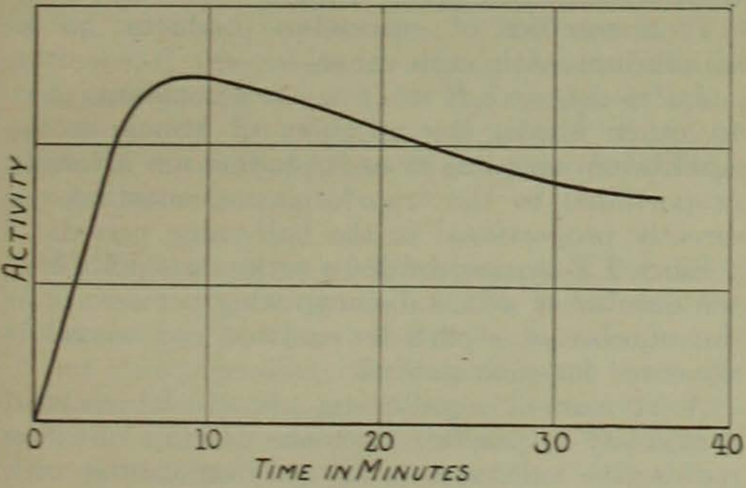

FIG. 24.—GROWTH OF ACTINIUM-C FROM ACTINIUM-B

As an example, the growth of actinium-*C* from actinium-*B* is shown in Fig. 24. The half-value period of actinium-*B* is 36·1 minutes, and that of actinium-*C* is 2·15 minutes. The amount of actinium-*C* reaches a maximum in 9 minutes and after about 20 minutes decays with a period of 36·1 minutes, the period of actinium-*B*.

It is to be noted that if the periods were interchanged the same curve would be obtained. Thus from such a curve the two periods can be deduced, but to decide to which product each belongs the second product must be obtained alone.

46. Radioactive Equilibrium. A product B of Q atoms is said to be in radioactive equilibrium with its parent substance A of P atoms when its decay is exactly compensated by its production from A, i.e. when $\lambda_1 P = \lambda_2 Q$.

If a number of successive products be in equilibrium with each other—

$$\lambda_1 P = \lambda_2 Q = \lambda_3 R = \ldots\ldots = \text{a constant.}$$

In other words, the numbers of atoms in the equilibrium amounts of each product are inversely proportional to the transformation constants or directly proportional to the half-value periods.

Since λN is constant for a series in equilibrium, the number of atoms disintegrating per second or the number of α-particles emitted per second is the same for each product.

A permanent equilibrium cannot be realized completely in practice since the amount of every radioactive substance is always diminishing with time. A very close approximation is attained, however, when the primary source transforms so slowly that its amount does not change appreciably during the time required by its products to reach approximate equilibrium.

For example, take the case of radium and radium-emanation, the periods of which are 1,800 years and 3·85 days respectively. The emanation approaches its equilibrium value very closely after a growth of two months, during which time the amount of radium decreases by only 0·007 per cent. Equilibrium of this kind is known as *secular equilibrium*.

When the amount of the primary source is not sensibly constant we have a case of *transient equilibrium*, which may be illustrated by the case of actinium-B and -C (§ 45, Fig. 24). At the maximum value $\lambda_1 P = \lambda_2 Q$, and for that moment the products are in true equilibrium. Finally, the amounts of both products decay exponentially with the same period. They are then said to be in *transient* equilibrium. The amount of actinium-C present is clearly greater than the true equilibrium amount, for the number of atoms of actinium-C breaking up per second is greater than the number of atoms of actinium-B breaking up per second.

47. Determination of Transformation Constants.

The direct determination of the transformation constant by the decay of activity of the product is not always possible. In the first place the radiation emitted by the product may be too weak for accurate measurement, and secondly the rate of transformation may be so slow that the change of activity over a reasonable period of time cannot be detected. The rate of transformation must then be determined indirectly. Some of the methods employed will be illustrated by the aid of examples.

(*a*) *Period of Actinium-B.* By exposing a plate for a few seconds to actinium-emanation a deposit of actinium-B only is obtained on the plate. Actinium-B emits only a weak β-radiation, but grows actinium-C which emits α-rays. The growth of actinium-C is followed by the α-ray activity of the plate and the curve of Fig. 24 is obtained. From this the two periods are deduced. Actinium-C is then obtained alone, and it is at once clear that the short period of 2·15 minutes belongs to this product. The period of actinium-B is therefore 36 minutes.

(*b*) *Period of Radium.* The number of α-particles emitted per second by 1 grm. of radium has been counted and is $3{\cdot}4 \times 10^{10}$. Hence if N is the number of atoms in 1 grm. of radium, $\lambda N = 3{\cdot}4 \times 10^{10}$ where λ is measured in $(\text{sec.})^{-1}$. Since the atomic weight of radium is 226 and the number of molecules in a gram-molecule is $6{\cdot}07 \times 10^{23}$, $N = 6{\cdot}07 \times 10^{23}/226$, and $\lambda = 1{\cdot}26 \times 10^{-11}\ (\text{sec.})^{-1}$, whence the half-value period $T = 1{,}730$ years.

(*c*) *Period of Uranium*-1. If P and Q be the numbers of atoms of uranium-1 and radium in a mineral in equilibrium

$$\lambda_{Ur} P = \lambda_{Ra} Q.$$

It is found by chemical analysis of uranium minerals that $3{\cdot}3 \times 10^{-7}$ grm. of radium is the equilibrium amount for 1 grm. of uranium.

$$\text{Hence } \lambda_{Ur} = \lambda_{Ra}\ (238/226 \times 3{\cdot}3 \times 10^{-7})$$
$$= 4{\cdot}4 \times 10^{-18}\ (\text{sec.})^{-1}$$

on inserting the value of λ_{Ra} found above.

Thus the half-value period of uranium-1 is 5×10^9 years.

(*d*) *Period of Thorium-C'.* It will be seen later (§66) that there is an approximate relation between the rate of transformation of an α-ray product and the range of its α-particle. This relation is of value when the rate of transformation of a product cannot be obtained in any other way.

For example, the period of thorium-*C′* is so short that no separation from thorium-*C* has been effected. Its period deduced from the range of its α-particle is of the order 10^{-11} sec. Again, uranium-1 and uranium-2 have identical chemical properties. The ranges indicate that uranium-2 has a much shorter period, about 2×10^6 years, than uranium-1. Consequently the assumption in (*c*) that uranium consists almost entirely (99·96 per cent.) of uranium-1 is justified.

48. Branch Products. In the majority of radioactive changes the atom breaks up in one way only; thus, an atom of radium-*A* emits one α-particle and forms one atom of radium-*B*. Some cases are observed, however, where an atom *A* breaks up in two different ways, giving rise either to an atom *B* or to an atom *B′*. In all cases except one the change of *A* into *B* takes place with the emission of an α-particle, whereas the change of *A* into *B′* is accompanied by emission of a β-particle. The most striking case occurs in the transformation of thorium-*C*, which is according to the scheme shown in Fig. 25.

On the average about one-third of the atoms of thorium-C breaks up with the emission of α-rays of range 5 cm., and forms an atom of thorium-*D*. The other two-thirds break up with the emission of a β-particle forming a body thorium-*C′* which emits the swiftest α-particles known.

Both radium-*C* and actinium-*C* are also complex, but in these cases the amount of the branch is very small. Thus out of every 10,000 atoms of radium-*C* only 3 break up with the emission of a β-particle and the formation of the branch product radium-C_2; and only 2 out of every 1,000 atoms of actinium-*C* change into the branch product actinium-*C′*. The scheme of disintegration is given in Fig. 27.

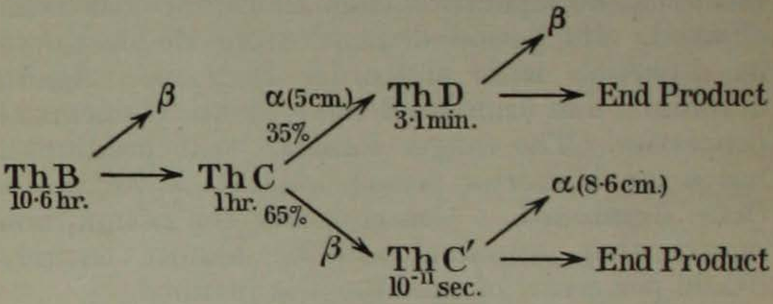

Fig. 25.—Diagram showing Complex Nature of Thorium-C

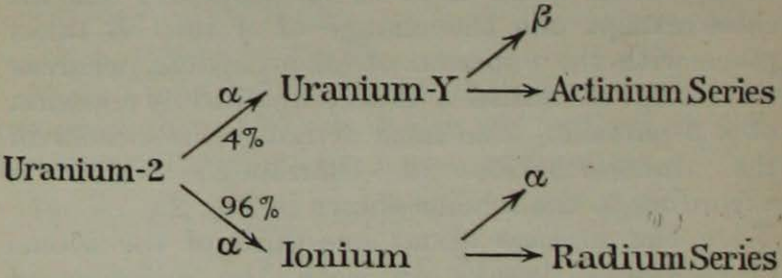

Fig. 26.—Diagram showing Branching of the Actinium Series from the Uranium Series

The case of uranium *Y* is of special interest, since this probably forms the starting point of the actinium series (*see* Fig. 27). Uranium-*Y* arises from the transformation either of uranium-*I* or of uranium-2. There is no evidence on this question, and uranium-2 is generally chosen as the branching point. The mode of disintegration is shown in Fig. 26.

About 4 per cent. of the atoms of uranium-2 change into uranium-*Y*, and the others into onium, in both cases with the emission of α-particles.

There is another possible mode of multiple disintegration, e.g. an atom A may break up and give *both* an atom B *and* an atom B'. No evidence of this has been observed.

CHAPTER VII

THE RADIOACTIVE SUBSTANCES

49. Radioactive Families. The radioactive substances are usually divided into three families—the uranium family, the actinium family, and the thorium family. It is probable that the actinium series is a branch of the uranium family, so that there are then only two primary sources, uranium and thorium.

The series of products arising from the transformations of uranium and thorium are shown in Fig. 27 ; the arrows show the direction of change. In this diagram it is assumed that the actinium branch takes place at uranium-2 through the product uranium-Y.

As explained in § 6, the α- or β-particle is emitted from the nucleus of a radioactive atom, the charge of the resulting nucleus being two units less or one unit more according as an α- or β-particle is expelled. Thus uranium-1 of nuclear charge 92 units emits an α-particle, and the product uranium-X has, therefore, a nuclear charge of 90 units. The successive changes in the nuclear charge resulting from the series of transformations are shown in the diagram.

50. Isotopes. Since the magnitude of the nuclear charge determines completely the ordinary chemical and physical properties of the atom, atoms of the same nuclear charge have identical chemical properties, and differ only in atomic weight. Thus all substances in the same horizontal row of Fig. 27 have the same chemical properties, and

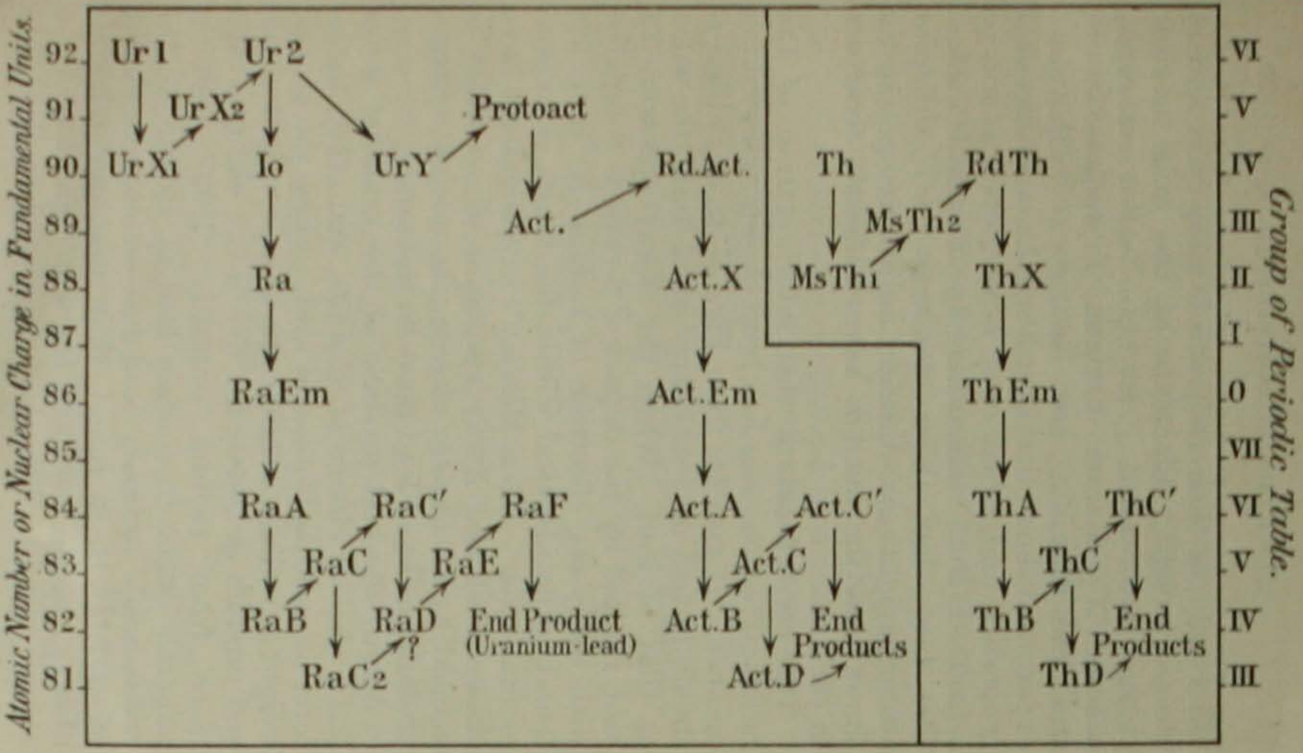

FIG. 27.—THE SEQUENCE OF THE RADIOACTIVE TRANSFORMATIONS

differ only in their radioactive properties and in atomic weight. Elements of the same nuclear charge are called "isotopes." For example, uranium-X_1, ionium, uranium-Y, radioactinium, and radiothorium are isotopes of thorium; experiment shows that they have the same chemical properties and, when once mixed, one cannot be separated from the other by chemical means. The fact that these elements have different atomic weights and different radioactive properties shows that the nucleus has a different structure in each case.

The correctness of this interpretation of the radioactive processes has been shown in a striking manner. It appears from Fig. 27 that radium-B should have a nuclear charge of 82 units, the same as that of lead. When the X-ray spectrum of lead, excited by the impact of β-rays, is compared with the γ-ray spectrum of radium-B, they are found to be identical within the limits of experimental error. Since Moseley's investigations have shown that the X-ray spectrum of an atom is defined by its nuclear charge, the nuclear charges of radium-B and lead must be the same.

Again, the end product of the uranium series has a nuclear charge of 82 units, and must, therefore, be another isotope of lead. Since the atomic weight of radium is 226·0, the atomic weight of the end product is 206·0, for five α-ray changes take place from radium onwards. Thus uranium minerals ought to contain lead of atomic weight 206·0, while ordinary lead has an atomic weight of 207·1. It is found that uranium minerals always contain lead, and the determination of the atomic weight of the lead separated from a pure specimen of pitchblende gave a value of 206·05. Further, this lead gave the same light spectrum as ordinary lead. Similarly, the end-product of the thorium series ought to be a lead of atomic weight 228, and this conclusion also has been fully borne out by experiment.

51. General Chemical Properties. A large number of the radioactive substances are isotopes of well-known elements, and their chemical properties are best defined in terms of these. Thus—

Uranium-1 Uranium-2	are isotopes of the common element	Uranium
Thorium, Radiothorium, Uranium-X_1, Uranium-*Y* Ionium, Radioactinium	,,	Thorium
Radium-*E*, Radium-*C* Thorium-C, Actinium-*C*	,,	Bismuth
Radium-*B*, Radium-*D* Thorium-*B*, Actinium-*B* and the end products	,,	Lead
Radium-C_2, Thorium-*D* Actinium-*D*	,,	Thallium

The chemical properties of the other radioactive substances are most simply defined by the nearest element in the same group of the periodic table. The number of the group is given on the right of Fig. 27. Thus—

Radium, Thorium-*X*, Mesothorium-1, Actinium-*X*	resemble in chemical properties	Barium
Radium-Emanation Thorium-Emanation Actinium-Emanation	,,	Xenon
Actinium, Mesothorium-2	,,	Lanthanum
Protoactinium, Uranium-X_2	,,	Tantalum
Radium-*A*, Radium-C', Radium-*F* Actinium-*A*, Actinium-C', Thorium-*A*, Thorium-C'	,,	Tellurium

52. Methods of Separation. A radioactive substance may be isolated from others (not isotopes) in one of the following ways—

(*a*) By ordinary chemical methods.
(*b*) By electrolysis or electrochemical methods.
(*c*) By differences in volatility.
(*d*) By recoil.

The last three methods are applied as a rule only to the products *A*, *B*, *C*, etc., which result from the transformation of the emanations.

The separation by chemical methods may be divided into three cases. If the radioelement is present in visible quantity the separation is carried out in the usual way. For example, radium may be precipitated by the addition of sulphuric acid, or a soluble sulphate, and recovered by filtration.

As a rule, however, the amount of the radioelement is extremely small, e.g. the weight of thorium-*X* in equilibrium with 1 grm. of thorium is 7×10^{-13} grm., and can only be detected by its radioactivity. In such cases a visible quantity of an isotope of the substance may be already present, and the radioelement will be obtained mixed with this isotope. As an example, we may take the separation of radium-*D* from a uranium mineral. The amount of radium-*D* present is very small, but its isotope, the end product or uranium-lead, is present in visible amount. This can be precipitated by sulphuretted hydrogen, and the precipitate dealt with in the usual way. The radium-*D* is divided between precipitate and solution in exactly the same proportions as the uranium-lead.

If no isotope is present in the material to give a visible precipitate, a small quantity (a few milligrams), either of an isotope or of a substance of similar chemical properties may be added. For example, the radiothorium grown in a preparation of mesothorium may be precipitated by ammonia as hydroxide. To give a visible precipitate one or two milligrams of its isotope thorium, or of iron, may be added.

53. Radioactive Properties of the Substances. The radioactive properties of most of the radioelements have been investigated in detail. Their rates of transformation have been determined, and the character of their radiations investigated. For a full account of this work the reader is referred to Rutherford's *Radioactive Substances and their Radiations*. The main results are tabulated in the Appendix. It will be noticed that in three cases, those of radium, actinium, and radioactinium, the data of the tables do not agree with Fig. 27. Both radium and radioactinium emit β-rays, although in relatively small amount, while in Fig. 27 provision is made only for the emission of α-particles. It must be assumed either that these bodies contain an unknown branch product of small amount which emits β-rays, or, more probably, that these β-particles do not come from the nucleus of the atom, but from the external system. In the third case, it was assumed in Fig. 27 that actinium emitted a β-radiation. This has not yet been observed. At one time many products were thought to be rayless, but subsequent work has shown that all, except actinium, emit β-rays, so that it is probable that actinium will be brought into line later.

Consideration of the tables of the Appendix and of Fig. 27, reveals a striking analogy between the three radioactive series. From the corresponding points ionium, radioactinium, and radiothorium the transformations run parallel. The transformation periods change from product to product in much the same way in all three series. This similarity in the modes of disintegration of products of different series promises to throw light on the nature of the processes which lead to the disintegration of the radioactive atoms, but no explanation has yet been offered.

54. The Emanations and the Active Deposits. Each series contains an emanation followed by an active deposit of short life, the corresponding members of which are isotopes and very similar in radioactive properties. The emanations are radioactive gases, chemically similar to the inert gases. They obey the ordinary laws of gases, diffuse at a rate corresponding to their high atomic weights, are absorbed by liquids to varying degrees, and condense at temperatures around –150°C.

Their chief importance lies in the fact that from them the active deposits can be obtained in a pure state, i.e. in an extremely thin layer free from admixture with ordinary matter.

If a preparation of radiothorium or actinium be placed on the bottom of the vessel *V* (Fig. 28), some of the emanation diffuses out and breaks up in the air inside, the active deposit settling on the walls of the vessel. If a rod *R* be connected to the negative pole of a battery of about 200 volts, and the vessel to the positive pole, it is found that the greater part of the active deposit is then concentrated on the rod *R*. Both actinium-*A* and thorium-*A* have such short periods that they hardly exist apart from the emanation. The rod *R* thus becomes coated with an invisible layer of atoms of the products *B* and *C*.

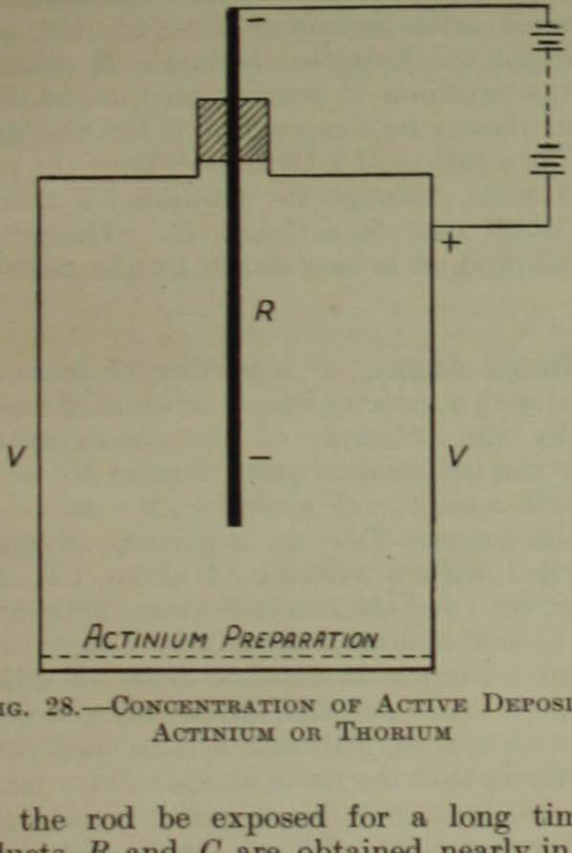

FIG. 28.—CONCENTRATION OF ACTIVE DEPOSIT OF ACTINIUM OR THORIUM

If the rod be exposed for a long time, the products *B* and *C* are obtained nearly in equilibrium with each other, but if the rod be exposed for a short time only, the *B*-product is obtained pure. Therefore, when the rod is examined by the electroscope the α-ray activity is zero initially, but grows rapidly owing to the formation of the C-product.

The curve showing the growth of actinium-C from actinium-B (Fig. 24), shows that the active deposit of actinium consists of at least two products of periods 36 mins. and 2·15 mins. If the rod coated with actinium-$(B + C)$ be heated to a bright red heat the actinium-B volatilizes while the actinium-C remains on the rod. The rod thus retains its α-ray activity, but this decays now with a period of 2·15 mins. Thus the period of 2·15 mins. belongs to actinium-C, and the period of 36 mins. to actinium-B. The presence of the D-product is best shown by the method of recoil.

55. Recoil Atoms. If a particle of mass m be expelled with a velocity v from an atom of mass M, then, by the principle of the conservation of momentum, the residual atom of mass $M - m$ must recoil with a velocity V given by $(M - m) V = mv$.

In the present case an α-particle of mass 4 is expelled with a velocity of about $1{\cdot}8 \times 10^9$ cms. per sec., and the residual atom, actinium-D, has an atomic weight of about 210. Consequently, when an α-particle is expelled from an atom of actinium-C the residual atom of actinium-D recoils with a speed of about $3{\cdot}4 \times 10^7$ cms. per sec.

It is found that the recoil atoms carry a positive charge and that they can be collected on a negatively charged plate. Thus a negatively charged plate brought near a parallel plate coated with actinium active deposit will collect some of the recoil atoms of actinium-D. After a few minutes exposure, the plate shows a strong β-ray activity which decays with a period of 4·7 minutes. Thus actinium-D is a β-ray product with the above period.

This method of separation by recoil has been of great value and some of the radioactive substances were discovered in this way.

The thorium active deposit may be investigated in the way indicated above for the actinium active deposit.

CHAPTER VIII

RADIUM AND ITS PRODUCTS

56. Radium. The peculiar importance of radium is due to the fact that it can be separated easily from uranium minerals and obtained in a pure state, and in such quantities that its properties have been examined by the usual chemical methods. For each gram of uranium in a mineral in equilibrium there is present $3{\cdot}3 \times 10^{-7}$ grm. of radium. Thus, 1 grm. of radium is present in 5,000 kg. of a mineral containing 60 per cent. of uranium.

The radium is separated from the mineral by a process similar to that for separating barium and is obtained as chloride, mixed with a relatively large amount of barium chloride. The radium chloride is then separated from the barium chloride by a process of fractional crystallization, the radium chloride being less soluble than the barium salt and crystallizing out first. In practice from 80 to 90 per cent. of the theoretical quantity of radium is obtained.

Radium behaves chemically as a higher homologue of barium. It forms a series of salts analogous in properties to those of barium ; the radium salts are in general less soluble than the corresponding barium salts. Radium has been obtained in the metallic state by electrolysis. The metal is pure white in colour, and melts at about 700°C. An accurate determination of the atomic weight was made by Hönigschmid, who found it to be 226·0.

Radium transforms with a period of about 1,750 years into the emanation, and emits a-rays, of range 3·30 cm. in air at 15°C, and a weak β-radiation. This β-radiation is of interest, for reference to Fig. 27 shows that the change of the radium atom into the emanation atom should be a pure a-ray change. We must assume either that radium consists of two products, one emitting a-rays and changing into the emanation, and the other emitting β-rays changing into some unknown product; or, as seems more probable, that these β-particles do not come from the nucleus of the radium atom but from the external system.

57. Radium Emanation. The emanation is an inert gas similar in all except radioactive properties to the ordinary inert gases such as neon and argon. It is produced at a practically constant rate from radium. In a radium preparation initially freed from emanation the emanation will grow according to the equation—

$$Q = Q_m (1 - e^{-\lambda t}) \text{ (\textit{see} § 44)}$$

where Q is the amount produced in a time t, and Q_m is the final equilibrium value. The period of the emanation is 3·85 days, and λ is, therefore, 0·180 $(\text{day})^{-1}$. Thus, the quantity of emanation reaches half value in 3·85 days, 75 per cent. in 7·7 days, and practical equilibrium in a month.

In a solid preparation of radium, most of the emanation is occluded, and only a small fraction escapes. The emanation can be released by heating the preparation or by dissolving and then boiling the solution.

58. Separation of Emanation. The best method of collecting the emanation grown by a radium preparation is by means of an arrangement similar

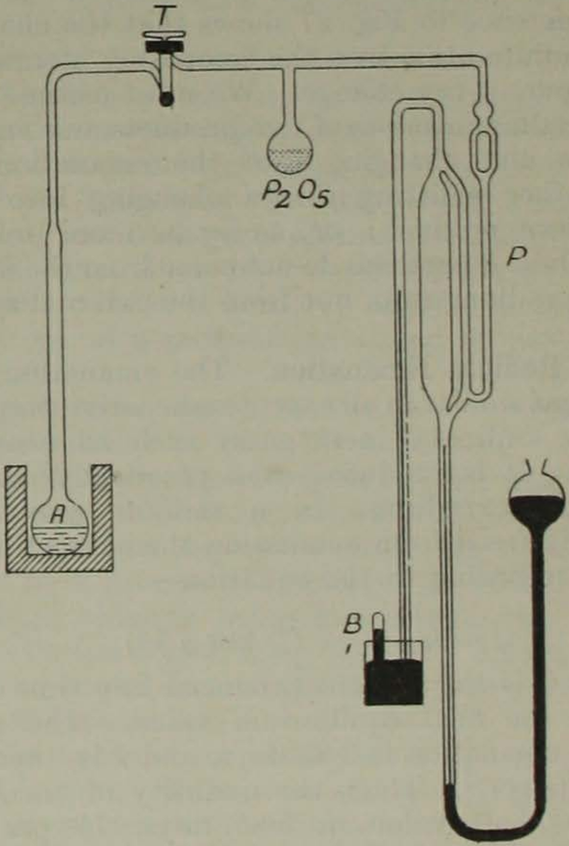

FIG. 29.—PUMP FOR COLLECTING RADIUM EMANATION.

to that shown in Fig. 29. The radium salt is kept in solution in the bulb *A*. The gases given off by the solution are pumped out by the Toepler pump *P*, and collected over mercury in the tube

B. The radiations emitted by the radioactive bodies decompose water into hydrogen and oxygen, 1 grm. of radium in solution producing about 15 cu. cm. of mixed gases per day. Thus a considerable quantity of gas may collect in the bulb *A* and its connections.

When the emanation is required the tap *T* is turned and the gases are allowed to expand into the pump. The tap *T* is then closed, and the gases are collected in the tube *B*. This process is repeated until the whole of the gas is removed. Most of the water vapour in the gas is removed by the P_2O_5 in the drying bulb. The gases pumped off in this way contain, besides the emanation, hydrogen, oxygen, helium (from the α-particles), and some carbon dioxide produced by the action of the emanation on the grease of the tap. The electrolytic gases are removed by introducing the gas into a mercury pipette, and exploding by passage of an electric spark. The residual gas is then transferred to a tube containing caustic potash, which removes the carbon dioxide. As a rule, the volume of the gas will now be about 0·1 cu. cm. and the purification has been carried out as far as is usually necessary. The emanation can now be used for the preparation of active sources.

The further purification of the emanation can be carried out by condensation in liquid air. The emanation condenses at about –150°C. and the uncondensed gases, e.g. hydrogen and helium, are pumped off. The complete purification is a matter of some difficulty, for the volume of the emanation is very small, being seldom more than 0·1 cu. mm.

59. Volume and Density of the Emanation. The amount of emanation in equilibrium with 1 grm. of radium is called a "curie," in honour of M. and Mme. Curie. The volume of the curie can readily be calculated. Each radium atom emits an α-particle, and becomes an atom of emanation. Since 1 grm. of radium emits $3{\cdot}4 \times 10^{10}$ α-particles per second, the number of emanation atoms formed per sec. is $p = 3{\cdot}4 \times 10^{10}$. When equilibrium is reached the number of atoms of emanation present is $Q_m = p/\lambda$ (*see* § 44). Since $\lambda = 2{\cdot}08 \times 10^{-6}$ (sec.)$^{-1}$, $Q_m = 1{\cdot}63 \times 10^{17}$. Now the number of molecules in 1 cu. cm. of gas at normal temperature and pressure is $2{\cdot}71 \times 10^{19}$. Therefore, if the emanation is a monatomic gas, the volume of the curie is 0·60 cu. mm.

The volume of the emanation in equilibrium with a known amount of radium has been measured by various observers. The mean value obtained for the volume of the curie is 0·60 cu. mm., in remarkable agreement with the calculated value.

The density of the emanation has been measured by Gray and Ramsay, using a micro-balance, which would detect a weight of one-millionth of a milligram. Their results gave a mean value of 223 for the atomic weight, in good agreement with the theoretical value. The radium emanation is thus the heaviest gas known, having a density 111 times that of hydrogen.

60. The Active Deposit. The active deposit of radium consists of six successive products, *A*, *B*, *C*, *D*, *E*, and *F*. The product radium-*D* has a ong period of transformation, about 17 years, so that in a recently prepared radium salt or in a tube containing emanation the amounts of *D*, *E*, and *F* are very small. We may, therefore, neglect these products at present and consider only the products *A*, *B*, and *C*, the active deposit of rapid change. The sequence of changes from the emanation to radium-*C* and the radiations emitted are shown graphically in Fig. 30.

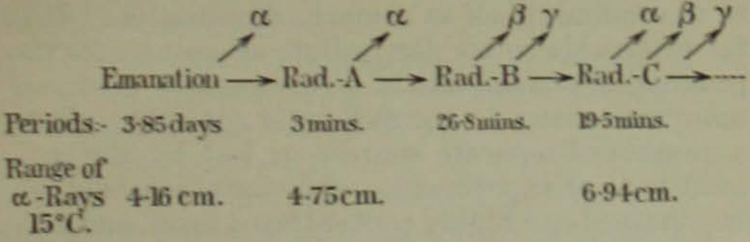

FIG. 30.—DIAGRAM SHOWING CHANGES FROM RADIUM EMANATION TO RADIUM-C

The term radium-*C* is generally used to include all three products C, C', and C_2, and the radium-*C* in the diagram may be considered as one product emitting α-, β-, and γ-rays.

The active deposit of radium can be obtained by exposing a negatively charged rod or plate to the emanation, and can be examined by the usual methods. Radium-*B* volatilizes from a metal wire far more readily than radium-*C*, and the products can be separated in this way. A very useful method of obtaining radium-*C* is by dipping a nickel plate into a solution of the active deposit in weak hydrochloric acid. A large part of the radium-*C* in the solution deposits on the nickel in a pure state.

61. Preparation of Sources of Radiations. It is clear that, when a quantity of radium is in equilibrium with its products, the radiations are due almost entirely to the emanation and active deposit. For each α-particle emitted by the radium itself, three are emitted by the emanation and active deposit, and practically the whole of the β- and γ-radiations arise from radium-B and -C. It is thus unnecessary, for most experiments, to use radium itself as a source of radiation. It is far preferable to use the radium as a source for the production of emanation. This method possesses many advantages ; the radium is not split up into a number of separate sources or lost by use in a multitude of experiments, while the emanation can be obtained in a highly concentrated form, and may readily be transferred from one vessel to another.

In most radioactive laboratories the bulk of the radium is, therefore, kept in solution. The emanation is pumped off as required, and purified as described in § 58.

The emanation may be used in two ways: (*a*) The emanation may be introduced into a glass tube and sealed off. The activity of the emanation tube will increase rapidly owing to the formation of the products A, B, and C, and will reach a maximum after about four hours. After about 8 hours the products will be in transient equilibrium with the emanation, and the activity of the tube will decay with the period of the emanation, viz., 3·85 days.

Such a tube affords a strong source of radiations. The walls of the tube may be made so thin that the α-particles escape. An α-ray tube of this kind will emit three sets of α-particles, corresponding to the emanation, radium-*A*, and radium-*C*. As a general rule, the stopping power of the glass walls is about 2 cm., so that the maximum range of the α-particles which escape is about 5 cm. The β- and γ-radiations are due to radium-*B* and radium-*C*. The γ-radiation of radium-*B* is relatively weak and of small penetrating power, so that the activity of an emanation tube measured through a few millimetres of lead is due chiefly to the product radium-*C*.

The amount of emanation in a tube may be found by comparing its γ-ray activity with that of a radium standard (§ 62).

(*b*) The emanation may be used to obtain sources of radium $(B + C)$. The emanation is introduced into a small glass bulb in which a metal plate can be exposed. If the metal plate be charged negatively to about 200 volts the greater part of the active deposit collects on the plate. After an exposure of two to three hours the products are practically in equilibrium, and the plate may be removed. The plate is coated with an invisible layer of radium-*A*, -*B*, and -*C*. The radium-*A* transforms with a period of 3 mins., and in 20 mins. it has practically all vanished. The matter on the plate then consists of radium-$(B + C)$.

An active plate prepared in this way is a source of homogeneous α-rays of range 6·94 cm. at 15°C, emitted by radium-*C*. β- and γ-radiations are also emitted, and the amount of radium-*B* and -*C* on the plate may be measured by means of the γ-radiation (§ 62).

62. Comparison of Quantities of Radium. The quantity of radium present in a preparation may be measured most simply by the γ-ray method. We have seen that a radium preparation in equilibrium with its products of short life, emits a penetrating γ-radiation the intensity of which is proportional to the amount of radium present. This γ-radiation is emitted by the products radium-B and -C. The intensities of the γ-radiations are compared most conveniently by means of the electroscope. A γ-ray electroscope is used, similar to that described in § 17 (Fig. 9), the walls of the electroscope being of lead at least 3 mm. thick; the β-rays are then completely absorbed in the lead walls, and the ionization inside is due entirely to the γ-rays. The ionization current, observed as the rate of discharge of the electroscope, is then a measure of the intensity of the γ-rays, if precautions be taken to ensure saturation.

The radium preparation to be measured is placed at a convenient distance to one side of the electroscope, and the rate of leak of the electroscope is measured. The radium standard, consisting of a known amount of radium in a sealed tube, is placed in exactly the same position, and the leak is again measured. After deducting the natural leak of the electroscope, the ratio of the leaks gives the ratio of the amounts of radium in the preparations.

If a number of observations be taken, the amounts of radium may be compared in this way with an error of less than 1 per cent.

The same method may be used to compare quantities of radium emanation. When the products are in transient equilibrium with the emanation, the γ-ray effect is compared with that due to a radium standard, and expressed in terms of milligrams of radium. Since the γ-ray activity of the emanation decays exponentially with the period of the emanation, the amount of emanation present at any time after its separation may easily be calculated from one set of measurements.

Similarly the amount of active deposit obtained on a plate by exposure to the emanation may be measured by its γ-ray effect, and expressed in terms of milligrams of radium.

The official international radium standard consists of a known weight of pure radium chloride sealed up in a thin glass tube. It was prepared by Mme. Curie, and is preserved at the Bureau International at Sèvres, near Paris. Duplicate standards have been prepared and deposited in the various national laboratories.

CHAPTER IX

GENERAL RESULTS

63. Production of Helium. It has been shown that the α-particles emitted by all α-ray products are identical in nature, and consist of the positive nucleus of the helium atom. Consequently every radioactive product which emits α-particles during its transformation must give helium as a by-product in amount proportional to the rate of emission of α-particles. This conclusion has been confirmed by many observers, who have shown that helium is produced by radium emanation, ionium, polonium, and uranium, and also by thorium and actinium in equilibrium with their products. It is also in agreement with the well-known fact that helium is occluded in considerable quantities in uranium and thorium minerals.

The rate of production of helium by radium and its products can be calculated from the known rate of emission of α-particles. The number omitted by 1 grm. of radium in equilibrium with its products of short life is $13{\cdot}6 \times 10^{10}$ per sec. or $4{\cdot}31 \times 10^{18}$ per year. Since the number of atoms in 1 cu. cm. of helium at normal temperature and pressure is $2{\cdot}71 \times 10^{19}$, this corresponds to a production of 159 cu. mm. per year. Careful measurements of the rate of production of helium by a known amount of radium have been made by Dewar and by Rutherford and Boltwood. The production found by Dewar corresponded to an amount of 164 cu. mm. per year, and that by

Rutherford and Boltwood to 156 cu. mm. per year.

The observed rate of production is thus in good agreement with the calculated value. These experiments show in a most convincing way the atomic structure of matter, and from them we may deduce directly the number of atoms in a given volume or weight of helium ; for the number of atoms is counted directly, and the volume of the resulting gas is measured. It is clear that the value so obtained is in good agreement with that based on entirely different data.

The rate of production of helium by uranium and thorium minerals has also been measured with results in accord with the calculated amounts.

64. Age of Minerals. Since helium is only found in large quantity in old minerals rich in uranium or thorium, it is natural to suppose that this helium has all been produced by the transformations of the radioactive substances in the mineral. On the assumption that the rates of transformation of uranium and thorium have remained unchanged since the mineral was formed, we can calculate from the amount of helium present the interval of time which must have elapsed since the formation of the mineral. Provided that no helium was present initially, this calculation gives a minimum value for the age of the mineral, for some helium will have been lost by diffusion. Many of the primary radioactive minerals are very dense and compact, and it is probable that the loss of helium in this way has been comparatively small.

By this method it has been possible to form estimates of the age of geological strata. The values range from 8 million years (Oligocene) to 700 million years (Archaean period).

Another method of estimating the age of uranium minerals is afforded by their lead content, for, as we have seen, lead is the end-product of the uranium series. The assumption that all the lead found in a uranium mineral has resulted from the transformations is justified only when the atomic weight of the lead is determined and found to be 206; but in all cases the value of the age of the mineral found in this way will be a maximum value. The amount of lead formed in 1 year by 1 grm. of uranium is $1{\cdot}21 \times 10^{-10}$ grm. The age of the mineral will therefore be $8{\cdot}2 \times 10^9 \times Pb/U$ years, where Pb/U is the ratio of the amount of lead to the amount of uranium in the mineral. In this way it was found that a mineral of the carboniferous period had an age of 340 million years, while a mineral of the Pre-cambrian period had an age of 1,640 million years.

It has thus been possible to obtain from radioactive data direct information as to the time of geological periods and the age of the earth, on the assumption that during the intervals under consideration the rates of transformation of the radioactive bodies have remained unchanged.

65. Emission of Heat. When the radioactive atoms disintegrate, a considerable amount of energy is liberated in the form of radiations. On absorption of the radiations in matter their kinetic energy is transferred to the molecules of the matter and becomes manifest as heat. This emission of heat by radioactive bodies can be shown very simply. A tube containing a radium salt is placed with a thermometer in a Dewar flask, and an exactly similar tube containing a barium salt is placed with a thermometer in a similar Dewar flask (Fig. 31). The thermometer with the radium tube then indicates a higher temperature than that with the barium tube. An estimate of the rate of emission of heat by the radium can be obtained by placing a coil of wire of known resistance in the barium tube and measuring the current required to raise the temperature of the barium to that of the radium.

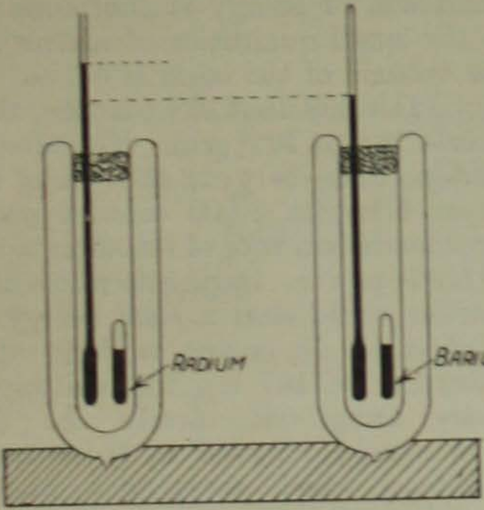

FIG. 31.—APPARATUS FOR DEMONSTRATING THE HEATING EFFECT OF RADIUM

By similar but more refined methods the rate of emission of heat of radium and its products has been measured. It is found that 1 grm. of radium in equilibrium with its products emits heat at the rate of 135 calories per hour; whilst 1 curie of emanation in equilibrium emits heat at the rate of 110 calories per hour. The greater part of this heating effect is due to the α-rays; only about 4·5 calories being due to the β-rays and about 6·5 calories to the γ-rays.

This emission of energy is enormous when we consider the small quantities of matter involved. Since the volume of the curie is 0·6 cu. mm. and its density 111 times that of hydrogen, the weight of the curie is 6×10^{-6} grm. Therefore 1 grm. of emanation emits energy at the rate of $1{\cdot}8 \times 10^7$ calories per hour, or 5,000 calories per second. This corresponds to a rate of emission of energy of about 28 horse-power. During its whole life, 1 grm. of emanation would emit a total energy equal to that supplied by an engine working at 28 h.p. for 5·6, days or at 157 h.p. for one day. These calculations bring out clearly the enormous amount of energy released in those radioactive transformations which are accompanied by the expulsion of α-rays. This energy is derived from the internal energy of the atoms. We have seen that the nucleus of a heavy atom consists of a large number of positively and negatively charged particles held together in a minute volume by intense electrical forces. The nucleus contains, therefore, a great store of electrical energy. This energy does not manifest itself in the ordinary way, for the chemical and physical forces hitherto available have failed to break up the atomic nuclei.

66. Relation between Range and Transformation Constant. Early in the development of radioactivity it was pointed out by Rutherford that there appeared to be a relation between the rate of transformation of a product and the velocity of the α-particle expelled from it; the shorter the period of transformation the greater the velocity

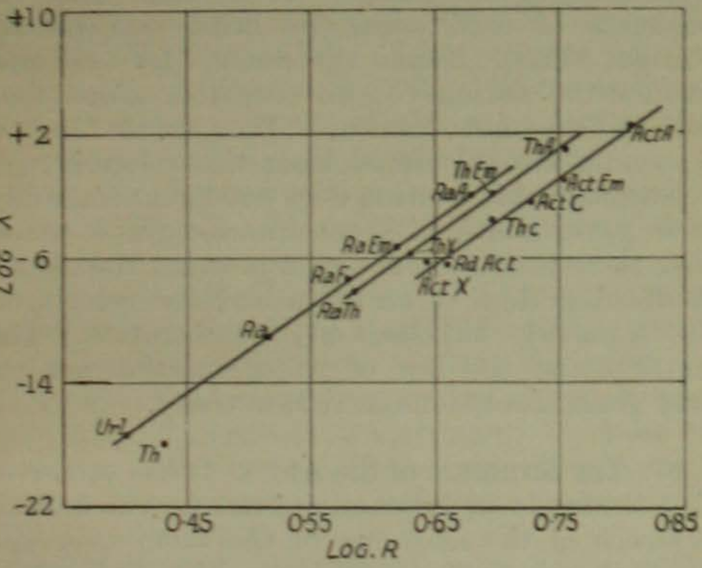

Fig. 32.—Relation between Transformation Constant and Range

of the α-particle. Later, Geiger and Nuttall examined this question by careful measurement of the ranges of α-particles expelled from all radioactive bodies, and obtained the relation—

$$\log \lambda = A + B \log R$$

where λ is the transformation constant of the product, R the range of the expelled α-particle, and A and B are constants. Since the velocity V

of the α-particle and the range R are connected by the relation $V^3 = aR$, we may write—

$$\log \lambda = A' + 3B \log V.$$

The relation is shown graphically in Fig. 32, where the logarithm of λ is plotted against the logarithm of the range. It is seen that the products of each series lie nearly on parallel straight lines. Some products, for example ionium and radium-C', are omitted, since their periods are not known. (The values in the Appendix are calculated from this relation.)

Although this relation does not hold accurately, it is nevertheless of great interest, for it shows that there is some connection between the chance of disintegration of an atom and the velocity of the α-particle expelled on disintegration. This relation and the law of transformation are the only general relations in radioactivity.

67. The Structure of the Atom. It has been seen that the study of radioactivity has provided direct evidence of the existence of the atom as a unit in the structure of matter. The radioactive processes show that the atom itself is complex, consisting of positively and negatively charged particles, and the investigation of the scattering of α-particles in passing through the atoms of matter has revealed the main constructional features of the atom, viz., a minute nucleus carrying a positive charge and an external distribution of electrons. The problem of the detailed structure of the atom then resolves itself into two parts—the question of the way in which the external electrons are arranged, and the question of the structure of the nucleus.

The phenomena of radioactivity are only indirectly concerned with the electronic distributions of the atoms. This part of the problem has been attacked with great success by Bohr. It appears that, on certain assumptions, the radiations, generally in the form of X-rays, emitted by the electrons near the atomic nucleus can be calculated. The investigation of the X-ray spectra of the elements should finally throw light on the arrangement of the inner rings of electrons, but at the present time little is known with certainty.

Both X-ray investigations and the experiments on the scattering of α-particles have shown that the electric force around the nucleus varies with the distance according to the well-known inverse square law, and that the magnitude of the charge on the nucleus is given in fundamental units by the atomic number, i.e. the number of the element when all the elements are arranged in order of increasing atomic weights. Thus the atomic number of hydrogen is 1, and that of aluminium is 13.

The scattering experiments also throw light on the dimensions of the nucleus, for the angle through which an α-particle is deflected depends on the distance at which it passes the nucleus of the scattering atom. It is found, for example, that the nucleus of the gold atom is of the order of 3×10^{-12} cm., about one ten-thousandth of the diameter of the atom. When we recollect that the nucleus of the gold atom has a mass 197 times that of hydrogen and a charge of 79 units, it is clear that the hydrogen nucleus must be of extraordinarily small dimensions. Information on this point has been obtained by the collision of α-particles with hydrogen nuclei. When α-particles pass through hydrogen there are very occasionally direct collisions between an α-particle and a hydrogen nucleus. Since the mass of the hydrogen nucleus is only one-fourth of the mass of the α-particle, it should be set into swift motion when hit directly by an α-particle. On the laws of momentum, the hydrogen nucleus, when hit directly, should acquire a velocity 1·6 times that of the α-particle. Such flying hydrogen nuclei have, in fact, been observed; their deflections in magnetic and electric fields have been measured, and the results show that the hydrogen nucleus carries unit positive charge, and on direct collision acquires a velocity 1·6 times that of the α-particle.

Investigation of the relations holding in these collisions leads to the conclusion that, in the case of a direct collision, the centres of the particles approach to a distance of about $3{\cdot}5 \times 10^{-13}$ cm. from each other. Bearing in mind that the α-particle, or helium nucleus, consists of four hydrogen nuclei held together by two electrons, it appears that the hydrogen nucleus must be small compared even with the negative electron. It seems probable, as we have assumed so far, that the hydrogen nucleus is the unit of positive electricity or positive electron, and its large mass may be attributed to the great concentration of its charge. On this assumption, the radius of the hydrogen nucleus would be about 10^{-16} cm., about 1/2,000 of the radius of the electron deduced on the same assumption.

In this way the minute size of the complicated gold nucleus receives some explanation.

The question of the actual structure of the atomic nuclei is one of the most important problems of modern physics. The emission of α-particles or helium nuclei in the radioactive transformations indicates that the helium nucleus is a secondary unit used in the structure of the nuclei of heavy atoms. The structure of the nuclei of the light atoms has already been attacked experimentally by Sir. E. Rutherford. For an account of these experiments the reader is referred to his Bakerian Lecture (1920).

We may observe that the fact that the helium nucleus survives the enormous forces which act upon it, in its ejection from the radioactive nuclei and in its passage through matter, shows that it has a very stable grouping. Its exact structure is, however, a matter for conjecture, for we have no information as to the nature and magnitude of the forces at the small distances concerned in the structure of the nucleus.

APPENDIX

THE RADIOACTIVE ELEMENTS AND THEIR CONSTANTS

TABLE V

URANIUM SERIES TO RADIUM

Substance.	Atomic Weight.	Weight per kilogram of Uranium.	Half-value Period.	Rays.
		milligrm.		
Uranium-1 . .	238	10^6	5×10^9 years	α
↓				
Uranium-X_1 . .	234	$1{\cdot}3 \times 10^{-5}$	23·5 days	β, γ
↓				
Uranium-X_2 . .	234	$4{\cdot}5 \times 10^{-10}$	1·17 mins.	β, γ
↓				
Uranium-2 . .	234	400 (?)	2×10^6 years (?)	α
↓ ↓				
Uranium-Y .	230	5×10^{-7}	25·5 hours	β
↓				
Ionium . . .	230	39 (?)	2×10^5 years (?)	α
↓				
Radium . . .	226	0·33	1,730 years	α, β

TABLE VI

Radium and Its Products

Substance.	Atomic Weight.	Weight per gram of Radium.	Half-value Period.	Rays.
Radium . . .	226	grm. 1	1,730 years	α, β
↓ Ra.-Emanation	222	$6{\cdot}1 \times 10^{-6}$	3·85 days	α
↓ Radium-*A* . .	218	$3{\cdot}3 \times 10^{-9}$	3·05 mins.	α
↓ Radium-*B* . .	214	$2{\cdot}9 \times 10^{-8}$	26·8 mins.	β, γ
↓ Radium-*C* . .	214	$2{\cdot}1 \times 10^{-8}$	19·5 mins.	α (?) or β, γ
β ↓ α Radium-C_2 .	210	$4{\cdot}5 \times 10^{-15}$ (?)	1·38 mins.	β, γ
↓ ↓ Radium-C′ . .	214	5×10^{-18} (?)	10^{-6} sec. (?)	α
Radium-*D* . .	210	$9{\cdot}2 \times 10^{-3}$	16·5 years	β, γ
Radium-*E* . .	210	$7{\cdot}6 \times 10^{-6}$	4·85 days	β, γ
Ra.F (Polonium)	210	$2{\cdot}1 \times 10^{-4}$	136 days	α

TABLE VII

THORIUM SERIES

Substance.	Atomic Weight.	Weight per kilogram of Thorium.	Half-value Period.	Rays.
		milligrm.		
Thorium . .	232	10^6	$1 \cdot 3 \times 10^{10}$ years	α
↓ Mesothorium-1 .	228	$5 \cdot 1 \times 10^{-4}$	6·7 years	β
↓ Mesothorium-2 .	228	$5 \cdot 2 \times 10^{-8}$	6·2 hours	β, γ
↓ Radiothorium .	228	$1 \cdot 5 \times 10^{-4}$	1·90 years	α
↓ Thorium-*X* . .	224	$7 \cdot 4 \times 10^{-7}$	3·64 days	α
↓ Th. Emanation .	220	$1 \cdot 2 \times 10^{-10}$	54·5 secs.	α
↓ Thorium-*A* . .	216	$3 \cdot 1 \times 10^{-13}$	0·14 sec.	α
↓ Thorium-*B* . .	212	$8 \cdot 5 \times 10^{-8}$	10·6 hours	β, γ
↓ Thorium-*C* . .	212	$7 \cdot 9 \times 10^{-9}$	60·8 mins.	α *or* β
α ↓β Thorium-*C′*	212	3×10^{-23}(?)	10^{-11} sec. (?)	α
↓ Thorium-*D* .	208	$1 \cdot 3 \times 10^{-10}$	3·1 mins.	β, γ

TABLE VIII

Actinium Series

Substance.	Half-value Period.	Rays.
Protoactinium	1,200–180,000 yrs.	α
↓ Actinium	about 20 years.	
↓ Radioactinium	19·5 days	α, β, γ
↓ Actinium-*X*	11·6 days	α
↓ Act. Emanation	3·92 secs.	α
↓ Actinium-*A*	0·002 sec.	α
↓ Actinium-*B*	36·1 mins.	β, γ
↓ Actinium-*C*	2·15 mins.	α *or* β
α │ ↓β Actinium-*C′*	5×10^{-3} sec. (?)	α
↓ ↓ Actinium-*D*	4·71 mins.	β, γ

The atomic weight of a member of the Actinium Series has not been determined. According to the transformation scheme of Fig. 27, the atomic weight of protoactinium should be 230.

TABLE IX

Atomic and Radioactive Constants

Charge carried by the hydrogen ion in electrolysis, i.e. fundamental unit of charge = $4{\cdot}77 \times 10^{-10}$ e.s. units

Number of atoms in 1 grm. of hydrogen = $6{\cdot}07 \times 10^{23}$

Mass of an atom of hydrogen = $1{\cdot}66 \times 10^{-24}$ grm.

Number of molecules per cc. of any gas at normal temperature and pressure = $2{\cdot}71 \times 10^{19}$

Value of e/m for α-particle = 4,823 e.m. units

Charge carried by the α-particle = $9{\cdot}54 \times 10^{-10}$ e.s. units *or* $3{\cdot}18 \times 10^{-20}$ e.m. units

Number of α-particles emitted per second by 1 grm. of radium itself = $3{\cdot}4 \times 10^{10}$

Number of α-particles emitted per second by 1 grm. of radium in equilibrium with its products of short life = $13{\cdot}6 \times 10^{10}$

Note.—More recent measurements of the number of α-particles emitted per sec. by 1 grm. of radium give a result of $3{\cdot}7 \times 10^{10}$.

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