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BEYOND THE ATOM

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PREFACE

THIS Essay is an attempt to tell in short compass the romantic story of the discoveries which within the last decade have led us beyond the atom. The great authorities and storehouses of fact are, of course, the books of Rutherford and (recently) Mme Curie on Radioactivity. Excellent statements of the main points are to be found in Strutt's *Becquerel Rays*, and Soddy's *Interpretation of Radium*. I have drawn upon all of them; upon the original papers in the current scientific periodicals; and also on my happy memories of those exciting times when for nine years I was privileged to witness at close quarters and discuss from day to day the work achieved by my friend and colleague Professor Rutherford in the Macdonald Physics Building of McGill University, Montreal, of which I was Director. Nor must I fail to express my special gratitude to Professor Rutherford for unstinted help and criticism while the work was passing through the press, without which, indeed, it could have had little value as an account of a subject still rapidly growing under his hands.

J. C.

February, 1913.

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PLATE. Tracks of α and β particles. *facing page* 142

CHAPTER I

Cox's *Beyond the Atom*

ERRATA

p. 35, ten lines from bottom, *should read*
The X-rays could **not** be reflected, &c.

p. 51, last word
'are' *should be* 'is.'

p. 60, line 13, *should read*
'just as the *activities* of Ur X, &c.', not 'action.'

p. 80, line 17
'Figure 7' *should be* 'Figure 8.'

Sumner founded the Royal Institution which, in
the opinion of good judges, has done more in the

century to advance physics than any single University or other body.

1802.—Wollaston first noticed the dark lines in the Solar Spectrum, thus laying the foundation of spectrum analysis.

1803.—Dalton brought forward the Atomic Theory, giving a vast expansion and impetus to Chemistry.

The turn of the nineteenth century has a group to match.

1878.—Crookes produced the Kathode Rays, claiming that they constituted a new, or fourth, state of matter—Radiant Matter.

1893.—Lenard, following up Hertz's discovery that Kathode Rays could pierce a thin sheet of metal, brought them outside the vacuum tube into the air.

1895.—Roentgen, repeating Lenard's work, discovered almost by accident the X-rays, and worked out their chief properties.

1896.—Becquerel discovered Radioactivity in uranium.

1897.—J. J. Thomson proved that the Kathode Rays consisted of particles a thousand times smaller than the atom of hydrogen, the smallest atom known.

1903.—Radium was discovered by P. and Mme Curie.

1896—1906.—Rutherford and Soddy established the Disintegration Theory of Radioactivity; thus founding a new science of Sub-atomic Chemistry.

The work of the intervening century brought to light some capital and many minor discoveries. Oersteút, in 1821, found the first connection between electricity and magnetism in the effect of a current on a neighbouring compass needle; Faraday, in a fortnight of marvellously fruitful work in 1831, laid bare the laws of the induction of currents. Later he found after many searches the first link between electricity, or rather magnetism, and light, and these regions were afterwards brought into one domain by Maxwell's Electro-magnetic Theory of Light which received a splendid verification in the experimental researches of Hertz.

But mainly the century was occupied with developing and correlating the leading ideas and discoveries which emerged at its birth. To realize the progress made, one must contrast the physical ideas current in 1800 and in 1900. In 1800 Mechanics had already reached a commanding development, and all explanation, even in the more backward sciences, was based on Newton's view of *action at a distance* as seen in gravitation. Sound and Light were indeed explained mechanically, sound by vibrations of the air, light by the impact of corpuscles. But Heat, Electricity and Magnetism were still isolated regions. Their mysterious properties were attributed to imaginary substances—

Caloric, the Electric Fluid, Magnetic Matter—which, because they did not affect the weight of the bodies in which they resided, were known as the *Imponderables*.

In 1900 Action at a distance is still employed as a useful figment in mathematical calculations. But the Imponderables are gone. Heat is molecular motion; light an ether vibration; magnetism ether whirls; electricity ether strain or ether shear. Matter itself may be vortex rings in the ether, or perhaps of electrical origin. Thus Mechanics has invaded the whole field, but it is the mechanics of molecules or of the ether. By extending the laws of motion derived from the study of bodies of sensible magnitude to the molecule and the ether, hypothetical entities for ever far beyond the limits of direct sense perception, a wonderful simplification has been effected.

The advance has been along two main roads, each lighted by a constellation of seven great names. One of these ways is through the Mechanics of Molecules, covering the theory of Heat and the Gaseous Laws. It was beaten out by Rumford, Mayer, Joule, Helmholtz, Carnot, Kelvin, Clausius. The other track lies through the Mechanics of the Ether, to the modern theories of Light, Electricity and Magnetism. Its pioneers were Young, Fresnel, Ampère, Faraday, Kelvin, Maxwell and Hertz. And

midway in the map of the century stand the two great landmarks :

Conservation of Energy ... 1847
Origin of Species ... 1859.

Insight into nature has grown by a process of deepening as well as widening, but above all of unification. It has been like the clearing of the mist to the watcher on a mountain top. Here and there the sun strikes a finger through it and touches into dazzling light the spires of a city, the silver bend of a river, or a blue gleam of the distant sea, set each in its frame of white vapour; and then at the sudden magic of some wandering air the curtain rolls off and leaves the landscape not only clearer where it could be seen before, but a rounded whole, right out to the circling horizon, the bearings of its separate details and their linked connections of road and river and railway spread like a map to the view. Here and there the curling wisps of cloud may still conceal a hollow in the hills or a sleeping lake; and always there is the baffling horizon, broadening the higher we rise, and impervious as ever to our gaze.

With this preliminary survey of the general course of physics in the nineteenth century, we shall now turn to the discoveries of the last decade, which are already seen to bear chiefly on the atomic structure of matter, and trace in outline the steps by which

physicists have been led to advance beyond Dalton's Atomic Theory and proceed beyond the atom.

Atomic theories date back at least to Democritus. Dalton's service lay in this, that he gave precision to the idea for the purposes of modern chemistry. When a chemical compound is formed the substance concerned will not unite in haphazard amounts, as in a mere mixture, but only combine in definite proportions. Thus nitrogen forms five different compounds with oxygen, in which 28 parts by weight of nitrogen are joined respectively with 16, 32, 48, 64 and 80 parts by weight of oxygen. The oxygen in the different compounds is for a given amount of nitrogen in the proportion of 1, 2, 3, 4, 5. Hence Dalton's view. The smallest amount of one of these compounds which could exist while still retaining the properties of the compound was called a *molecule* of that compound. The molecule was composed of *atoms* of nitrogen and oxygen. The atoms of nitrogen were all identical and had the same weight; and so for oxygen and all the other *elements*, or simple substances. The atom of hydrogen, the lightest, being taken as a standard, that of nitrogen weighed 14 and oxygen 16 times as much. For good reasons the compounds of nitrogen and oxygen were held to result from the union of two atoms of nitrogen (each 14) with 1, 2, 3, 4 or 5 atoms of oxygen (each 16). The law of definite or multiple proportions, as found

by experiment, was accounted for, and the chemist had a convenient means of describing, systematizing, and thinking about the complicated facts he had to deal with; which, indeed, is all that can be asked of a theory or working hypothesis. For, as Sir Joseph Thomson says, 'a theory is a policy rather than a creed.' For the purposes of the chemist the atomic theory is as serviceable to-day as it has been throughout the century, in spite of the modifications which the work of the last ten years has compelled in our conception of the atom.

Meanwhile the physicists employed the molecule (or in the case of elements the atom) to elucidate those properties of matter which fall short of chemical change. The facts of cohesion indicate that molecules can exert enormous forces of attraction on each other, but only when brought within inconceivably minute distances. Thus a broken solid cannot be mended by forcing the parts together by hydraulic pressure, however great. The molecules cannot be brought again within the range of their mutual attractions. To effect this fusion must be resorted to, or some cement which is able to come into such intimate contact at ordinary temperatures. On the other hand, the molecules are supposed to be in rapid motion, and the states of matter, as we know it by the senses,—solid, liquid and gaseous,—result from a balance between the attractive forces and the motions.

In solids the molecules, or at least most of them, are permanently anchored in fixed positions, locked together by their mutual forces; and yet are in perpetual agitation, either of vibration or rotation, about those positions. It may seem outrageous to claim that a block of gold or of lead, apparently so quiescent, is really the theatre of violent tremors and motions among its myriads of particles. But the senses are not safe guides. The eye cannot discriminate the spokes of a wheel in comparatively sluggish motion. And there is plenty of positive evidence that the molecules do travel, even in solids. If the block of gold be left in contact with the lead and examined from time to time, traces of each metal will presently be found throughout the other. Again, if, as Rumford showed, heat is motion, it must be molecular motion. The expansion of solids no less than liquids with rise of temperature is consistently explained if temperature corresponds to the average molecular energy of motion.

In liquids, though the bonds are partially relaxed and the molecules may slip freely over each other from one point to another, they are never far enough apart to escape the constraint of their mutual forces. The facts of evaporation and diffusion, much more marked than in solids, compel a belief in their mobility.

In gases at last the molecules are for most of their

time free from mutual constraint. Since a cubic inch of water occupies 1600 cubic inches when converted into steam, the spaces between the molecules must be very large compared with the size of a molecule. And since a vapour expands instantly to occupy any new space opened to it, the velocity of travel must be great. In fact a gas is conceived as a crowd of particles travelling at high speed for the most part in 'free paths,' perpetually interrupted by collisions or encounters with each other and with the sides of the containing vessel. The pressure on the vessel is the averaged result of the blows from the molecules which bombard it ; just as a high-pressure jet of water may be used in mining to cut away the side of a hill.

On this theory it has been possible to find consistent explanations, not only of the ordinary properties of matter, but of the main laws of gaseous pressure. These are (1) the law of Boyle, that the pressure of a gas is proportional to its density, and (2) the law of Charles and Gay-Lussac, that the pressure is proportional to the temperature of the gas measured from absolute zero.

More interesting from the point of view of this essay are the inferences which, conversely, have been drawn from known physical facts with regard to the molecules themselves. Different investigators, Loschmidt, Maxwell, Stefan, Stoney, Kelvin—starting from such apparently unconnected facts as diffusion,

viscosity and conduction of heat in gases, the thickness and surface tension of a soap bubble just before it breaks, and the electric action between thin layers of zinc and copper, have nevertheless arrived at results which are in fair agreement at least so far as the order of the magnitudes concerned. The numbers generally accepted for hydrogen and oxygen, for instance, are given by Maxwell as follows :

	Hydrogen	Oxygen
Mass of molecule (hydrogen = 1) ...	1	16
Velocity (of mean square) in metres per second at 0° C.	1859	465
Mean free path in millimetres ...	965×10^{-7}	560×10^{-7}
Collisions (millions per second) ...	17750	7646
Diameter (millimetres)	5.8×10^{-7}	7.6×10^{-7}
Mass (in grams)	46×10^{-25}	736×10^{-25}

About two million molecules of hydrogen in a row would occupy a millimetre, *i.e.* the twenty-fifth of an inch. Fifteen thousand million million million of them would weigh a grain. When the gas is at freezing-point each molecule makes on the average 17,750 million collisions per second at each of which its speed is changed and diverted. Yet on the average it has a speed of over six thousand feet per second, moving about a quarter of a millionth of an inch between collisions.

The number of molecules in a cubic centimetre of hydrogen is 3.8×10^{19} , or about six hundred million

million million per cubic inch. And this number holds for all gases, since one of the consequences of the kinetic theory of gases is Avogadro's law, that the number of molecules in a cubic centimetre at a given temperature and pressure is the same for every gas.

As to the structure of the atoms, the most tempting view in the seventies was the vortex-ring theory of Sir William Thomson, based on Helmholtz's investigation of vortex motion in a perfect fluid. Everyone knows the rings which can be blown by a skilful smoker. Even in a viscous fluid like air they show considerable permanence. But Helmholtz had proved that in a frictionless fluid, such rings can neither be created nor, if once in existence, destroyed. Each ring always consists of the same portion of the fluid, and its 'strength,' *i.e.* the product of its cross section by its velocity of rotation, remains the same. No ring can cut across another, or across any of its own convolutions. Hence if two rings are linked, they can never be separated, or if a ring is knotted on itself, it can never be untied. Moreover, two rings at an encounter exhibit attraction or repulsion according to their directions of rotation.

In these properties Thomson recognized many of the necessary characteristics of an atom. 'In the first place,' says Maxwell, 'the vortex ring is quantitatively permanent as regards its volume and its strength,—two independent quantities. It is also

qualitatively permanent as regards its degree of implication, whether "knottedness" on itself or "linkedness" with other vortex rings. At the same time it is capable of infinite changes of form, and may execute vibrations of different periods, as we know that molecules do. And the number of essentially different implications of vortex rings may be very great without supposing the degree of implication of any of them very high.'

There is a fascination about the vortex-ring theory because of the prospect of simplification it opens out. It unites the two main lines of research we have traced through the century, since the structure of matter is reduced to the properties of motion in a frictionless fluid which may be taken to be the ether. The atom is no longer a foreign body embedded in an alien medium, yet able to communicate vibrations to it; but is a portion of the universal ether itself, only differentiated, and yet permanently differentiated, from the rest by its mode of motion.

The position reached in the seventies may be summed up in a famous passage from Maxwell's article on the atom in the *Encyclopædia Brit.* 9th Ed. 1875. Having discussed the volume, mass and other characteristics of the molecule, or atom, including its rates of vibration as revealed by the spectroscope, and found them identical for all molecules of the same kind, he proceeds:

‘It is the equality of these space- and time-constants for all molecules of the same kind which we have next to consider. We have seen that the very different circumstances in which different molecules of the same kind have been placed have not, even in the course of many ages, produced any appreciable difference in the values of these constants. If, then, the various processes of nature to which these molecules have been subjected since the world began have not been able in all that time to produce any appreciable difference between the constants of one molecule and those of another, we are forced to conclude that it is not to the operation of any of these processes that the uniformity of the constants is due.

‘The formation of a molecule is therefore an event not belonging to that order of nature under which we live. It is an operation of a kind which is not, so far as we are aware, going on on earth or in the sun or the stars, either now or since these bodies began to be formed. It must be referred to the epoch, not of the formation of the earth or of the solar system, but of the establishment of the existing order of nature, and till not only these worlds and systems, but the very order of nature itself is dissolved, we have no reason to expect the occurrence of any operation of a similar kind.

‘In the present state of science, therefore, we have

strong reason for believing that in a molecule, or if not in a molecule, in one of its component atoms, we have something which has existed either from eternity or at least from times anterior to the existing order of nature. But besides this atom, there are immense numbers of other atoms of the same kind, and the constants of each of these atoms are incapable of adjustment by any process now in action. Each is physically independent of all the others.'

When this passage was written, the march of science had apparently reached a pause. During the century the whole field of natural knowledge had been for the first time systematically ransacked. The first rich harvest of great discoveries had been made; and here, with an alluring speculation it is true, the path of theory seemed to end in a barrier to further progress. It was excusable that many should feel there was little left for the future except to glean here and there an ear which had been overlooked or to conquer perhaps another decimal in the accuracy with which a physical constant was known. But in science less than anywhere is it safe to venture a negative, and the world was on the verge of discoveries which have given a Sophoclean irony to Maxwell's words.

CHAPTER II

THE VACUUM TUBE

EVER since the invention of the Induction Coil afforded the means of passing high-tension currents through partially exhausted tubes, anyone watching the strange and beautiful phenomena within the tube must have felt instinctively that here was the borderland of discovery, here if anywhere might be sought further light on the ultimate nature of matter and of electricity, and their mutual relation.

The terminals of the coil are joined up to *electrodes* of platinum wire fused through the glass. In Faraday's nomenclature the electrode by which the current enters, connected therefore to the positive terminal, is called the Anode : the negative electrode is called the Kathode. With a long tube of air at ordinary pressure no current will pass. But on partial exhaustion the current leaves the spark gap of the coil and takes to the tube, at first in the form of a narrow stream of crimson light. When the pressure is reduced to two or three millimetres of mercury, about one two-hundredth of an atmosphere, the Geissler vacuum is reached. The kathode is now seen to be encased in a thin dark space, outside

which is a glow of soft violet light. Then follows another dark space, and beyond it the tube is filled as far as the anode with flickering sheets of light—the *Striae*—separated by darker spaces. The anode itself is tipped with a vivid speck of light. The colour of the striae depends on the gas which last filled the tube. For hydrogen it is reddish, for nitrogen a deeper red, for carbonic acid a pale green.

It was Sir William Crookes who, in his celebrated lecture to the British Association in 1878, first brought prominently forward the results of carrying the vacuum much farther. As the pressure decreases the dark space about the kathode expands, driving the striae before it, until at a pressure of about a millionth of an atmosphere the dark space reaches the walls of the tube. The interior of the tube is then dark except for a faint cone of violet light which seems to shoot out from the kathode in straight lines; but the walls of the tube shine with a brilliant fluorescent light, yellowish green for ordinary glass, steel blue for flint glass.

Crookes showed a number of very beautiful tubes constructed to prove the following points :

(1) The faint violet light shoots out from the kathode at right angles to its surface, and proceeds in straight lines, like light, independently of the position of the anode; whereas at the lower vacuum the column of the striae bends round corners, even into

side-tubes, till it reaches the anode. Hence he gave this light the name of Kathode Rays.

(2) Where the rays strike they cause fluorescence, as on the walls of the tube. If a maltese cross of metal be set up within the tube in the path of the rays, it casts a shadow on the far end. Objects, such as diamonds, rubies, shells, minerals, exposed to the rays within the tube shine with brilliant and characteristic colours.

(3) The rays exert mechanical pressure. If directed on to light vanes attached to an axle, they can be made to turn little mills, or drive a wheel along glass rails, as in the 'railway tube.'

(4) They heat the object struck. By using a kathode shaped like a small concave mirror they may be converged on to a piece of platinum, which soon becomes red hot, and may even be fused.

(5) When a magnet is brought near the tube, the stream of rays is deflected, moving across the lines of force of the magnetic field in the same way as a *negative* current would do.

Crookes concluded that the kathode rays were streams of minute particles travelling at very high speed and each conveying a negative charge. If this were so, then two streams travelling side by side should diverge, owing to the mutual repulsion of their charges. In another tube this was shown to be the case. Crookes therefore held that the kathode rays

constituted a fourth state of matter, neither solid, liquid, nor gaseous, and called it Radiant Matter.

For nearly twenty years a controversy raged as to the nature of kathode rays. For the most part the English school held with Crookes that they were streams of particles ; with some difference of opinion whether they were fragments of the metal electrodes torn off by the violent electric forces, or, perhaps, the remainder molecules of the gas, now at liberty in the high vacuum to move with greater ease over longer free paths under the influence of the electric field.

In Germany it was maintained that they were not particles at all, but an ether phenomenon, of the nature of ultra-violet light. Perrin, however, proved that they carried a negative charge by receiving them in a small metal cylinder fixed within the tube and connected by a wire fused through the glass with an external electroscope. When the rays fell into the cylinder the electroscope showed a growing negative charge ; but when they were deflected by a magnet so as to miss the cylinder, the action ceased. In 1893 Lenard, following up an observation of Hertz that the rays could penetrate a thin sheet of metal, succeeded in bringing them outside the tube. A small window in the end of the tube was sealed with a thin foil of aluminium. It was only one thirty-fifth of an inch in diameter, so that the foil might stand the atmospheric

pressure. When the rays were directed on to the window, they issued through the foil into the open air.

Levard's experiment certainly favoured the English view, since the foil used was impervious to any form of light. But it was J. J. Thomson who in 1897 finally cleared up the nature of the kathode ray. His experiment, as ingenious as it was difficult, deserves special attention, since in principle it has been applied to test the nature of all the rays to be dealt with subsequently. The principle is based on Crookes' magnetic deflection experiment.

A particle carrying an electric charge projected across a uniform magnetic field at right angles to the magnetic lines of force is by known electric laws subject to a deflecting force perpendicular at each point to the direction in which the particle is moving. But this is a well known case of motion. A stone whirled round at the end of a string is subject to just such a force, since the string is always pulling it along the radius. The electric particle will therefore describe a circle like the stone. In fact with proper arrangements the kathode rays can be curled up into a circle within the tube, and the radius of the circle can be measured, or if the circle is not completed, its radius can be calculated from the observed curvature of the path.

Suppose that the kathode ray consists of particles each of mass m , carrying a charge e , at a speed v .

Then by exposing them to a known magnetic force, and observing the radius of the circle described, it should be possible to relate the quantities e , m , v . In fact, if H is the strength of the magnetic field and r the radius of the circle, we know from the laws of electricity that the deflecting force is $H \cdot e \cdot v$; and this must be the force required to make the particle go round a circle of radius r , which from elementary mechanics is known to be $\frac{mv^2}{r}$.

Thus
$$Hev = \frac{mv^2}{r}$$

and
$$\frac{e}{m} = \frac{v}{Hr}.$$

Since H and r are known numbers, we have a relation between the ratio, $\frac{e}{m}$, of the charge carried by a particle to its mass, and the velocity v with which the particle is moving.

To determine each of these quantities separately a second equation must be found. This has been done in several ways. One method employed by J. J. Thomson is the following, in which the magnetic deviation of the rays is compared with that produced by an electric field. The kathode rays from C are reduced by the diaphragms AB to a narrow pencil which passes between two electrified plates D , E and falls on a phosphorescent screen PP' . The negative

particles of the ray are repelled from the negative plate and attracted towards the positive by a force Xe , if X is the electric force between the plates.

A magnetic field (not indicated in the figure) is now applied, as in the previous experiment, in such a direction as to oppose the electric force, and its strength is varied till the spot of light P' is brought

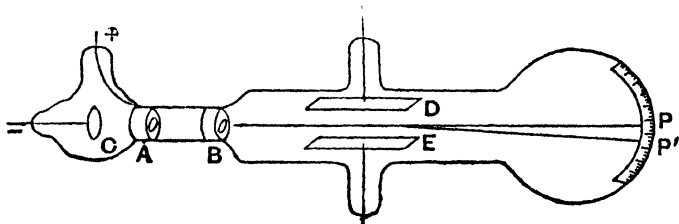


Fig. 1.

back to its undeviated position P . When this balance is effected,

$$Hev = Xe,$$

or
$$v = \frac{X}{H},$$

and when v is known, $\frac{e}{m}$ follows from the previous equation.

The results of this brilliant piece of work, confirmed in essentials by many subsequent investigations, were indeed surprising.

It appeared that the velocity of the kathode particles might range from one-thirtieth to one-third

the speed of light, *i.e.* from about 6000 to 60,000 miles per second according to the electric pressure applied to the tube, or the pressure and nature of the residual gas within it. These were astonishing speed limits. But even more significant was the fact that the ratio $\frac{e}{m}$ of the charge carried to the mass of the carrier particle, came out *the same, whatsoever the nature or pressure of the gas in the tube, or the metal used as kathode.*

While this result practically established the view that the kathode ray consisted of charged particles, it could no longer be supposed that the particles were either molecules of the gas or fragments torn off the kathode. The actual value of $\frac{e}{m}$ was about ten million (10^7) if e is measured on the electro-magnetic system of units.

Now there is a well known case in which 'ions' or travelling particles carry electric charges. In the electrolysis of water by the electric current the atoms of hydrogen and oxygen moving in opposite directions convey known quantities of electricity per gram of hydrogen or oxygen liberated. It is easy by comparing these quantities to show that for the atom of hydrogen, acting as carrier, $\frac{e}{m}$ is about ten thousand (10^4). The ratio for the kathode particle, ten million,

is thus about a thousand times greater than for the hydrogen atom in electrolysis.

There are only two possible explanations, or perhaps a third may be found in the combination of the two, though this is unlikely. Either the charge of the kathode particle is a thousand times greater than that of the hydrogen atom, the masses being the same; or, if the charges are the same, the mass of the kathode particle must be a thousand times less than that of the hydrogen atom, the smallest body hitherto known to science !

Before accepting either of these alternatives it is well to see if the strange facts of the kathode ray can be supported by other instances. This is the case. When we come to the study of radioactivity we shall make acquaintance again and again with charged particles for which this same high value of the ratio $\frac{e}{m}$ holds good. At the present stage we shall only adduce one singularly interesting piece of evidence which comes from quite a different quarter. In the last years of Faraday's life, when his memory was gone and his faculties were clouded, the arrival of a new Steinheil spectroscope at the Royal Institution brought him up from his retirement at Hampton Court to try for one more discovery. He set the source of light in a powerful magnetic field and examined the spectrum expecting some change in

the lines. The experiment was a failure. But we now know that his wonderful instinct had guided him to try all the right arrangements. Nothing was wanting for success except more power in the spectroscope, and thirty years later, in 1897, Zeeman applying the Rowland diffraction grating found the effect which Faraday looked for in vain. Certain lines are displaced, doubled, trebled, and in some cases split into six, and variously polarized. The Zeeman effect could be explained on Lorenz's theory of radiation, that the light vibrations were started by charged particles either moving in orbits or vibrating within the atom; and the resulting formula for the displacement of a line showed that it depended on the strength of the magnetic field and the ratio $\frac{e}{m}$ for the vibrating particle. A comparison of the formula with the observed displacements showed that the charge e must be negative and that the ratio $\frac{e}{m}$ for the light vibrators was again about 10^7 , the same as for the kathode particles.

It seems therefore impossible to doubt that there exist particles for which the ratio $\frac{e}{m}$ is 10^7 , or a thousand times greater than for the hydrogen atom in electrolysis.

Returning to our alternatives, are we to believe

that this is because the charge carried is a thousand times as great? Or that the mass of the carrier is a thousand times less than an atom of hydrogen? There is much presumptive evidence against the former view, evidence tending to show that electricity, like matter, is *atomic* in structure, *i.e.* that there is a definite minimum or unit charge of electricity, and that all other charges are multiples of this elementary 'atomic' or 'ionic' charge. Thus in electrolysis, when several cells containing different substances are joined up in series, so that the same current passes through each, through water in one, hydrochloric acid in another, copper sulphate in a third, silver chloride in a fourth, whatever the substance under decomposition, each 'ion,' whether atom or molecule, is found to carry the same 'ionic' charge. There are other ways of producing 'ions,' or charged particles. They are given off from the hot filament of an incandescent lamp, and from zinc exposed to ultra-violet light. As we shall see, they are caused by the passage of X-rays through a gas, and by the radiations from radioactive substances. J. J. Thomson has succeeded in measuring the charge associated with them in all these instances, and in every case it turns out to be this fundamental 'ionic' charge or some simple multiple of it.

The first case to be successfully attacked was that of the ions produced by X-rays. The charge carried by them was measured by Thomson in 1898, by

means of one of the most beautiful experiments ever devised, an experiment based on C. T. R. Wilson's work on the formation of clouds. Wilson had studied the conditions under which water vapour condenses into drops upon sudden expansion. A vessel filled with air standing over water, and therefore saturated with water vapour was arranged so that the space could be suddenly expanded by a measurable fraction of its volume. At first a very small expansion formed a cloud, for the vapour condensed upon the dust particles present. After several clouds had been formed and allowed to settle, so that the dust was all carried down into the water, no further condensation could be obtained in the dust-free air unless the space was expanded by at least a quarter of its volume. Then a few drops appeared, until the expansion reached rather more than one-third—from 1 to 1·38—when a dense cloud again appeared. Now it is possible to produce within the vessel 'ions,' *i.e.* small particles with an electric charge, such as are in question in the kathode ray and kindred phenomena, and Wilson had shown that these can act as nuclei for condensation as well as the dust particles. If they are present, then a cloud appears whenever the sudden expansion reaches the value 1·25, *i.e.* the original space is increased by a quarter of its volume. Thomson noticed that the cloud greatly increased in density when the expansion reached 1·31, and suggested that this was the point

when the positive ions came into action, the negative alone proving effective at the lower value 1.25. In another experiment Wilson succeeded in separating the negative and positive ions in the same vessel and proved that this was the case.

The next step was to count the number of droplets formed. This was effected by timing the rate at which the cloud in the vessel slowly settled down. For Stokes had given a formula for the rate of fall of a small sphere in a viscous gas like air, a formula which depended on its radius. From the observed rate of fall the *radius* of the droplets could thus be found. And since the total amount of water precipitated by a given expansion could easily be calculated, it was only necessary to divide this amount by the volume of a droplet, and the number of the droplets was found.

We are now prepared to understand how Thomson measured the charge on an ion. Two horizontal plates were fitted in Wilson's expansion vessel, and connected in circuit with a weak battery and a current-measurer. Ions were produced between the plates, and upon expansion the cloud was formed. Assuming that each droplet represented an ion, the ions could be counted. As they travelled to the two plates, positive and negative each seeking the plate of opposite kind, they carried a current round the circuit, and from its intensity, now that the number of ions concerned was known, the charge borne by each could at last be

determined. The value deduced by Thomson was

$$e = 3.4 \times 10^{-10} \text{ electrostatic units,}$$

approximately the same that is carried by the hydrogen atom in the electrolysis of water.

There were obvious difficulties and sources of error in Thomson's experiment which rendered his result liable to a variation of as much as thirty per cent. And it involved one assumption that required justification, viz. that all the ions were employed as nuclei and that no droplet contained more than one ion. This point was cleared up by an ingenious variation of the experiment due to H. A. Wilson, who compared the rate of fall of the cloud under gravity with its velocity under the influence of an electric field. When the electric field was applied the cloud at once separated into two or sometimes three clouds with different speeds corresponding to a single, double or triple charge. Some of the droplets can therefore absorb two or even three ions. Confining his observations to the cloud which carried the smallest charge Wilson deduced results which, though still subject to variations of as much as thirty per cent., gave a mean value for the ionic charge of $e = 3.2 \times 10^{-10}$ which was only slightly lower than Thomson's value 3.4×10^{-10} .

According to the most recent researches, based on radioactive phenomena and also on the theory of

radiation, this value is in fact about thirty per cent. too low, and Rutherford has made an interesting suggestion to account for the error. He attributes it to the fact that no allowance was made for *evaporation from the drops during the fall of the cloud*, so that their radius, as determined by Stokes' formula, would come out too small, their number consequently too great, and the charge carried by each too small again. To such minute points must the mind be alert in these difficult investigations. Patience and care will in the end attain accuracy in estimating the effect of any one factor; the task of genius is to divine what factors should be included, to watch that none be overlooked.

To obviate this error Millikan and Regener have repeated the experiment, using droplets of oil which are not subject to evaporation in the same way. Their results gave $e = 4.06 \times 10^{-10}$, in close agreement with the most recent values obtained otherwise.

The same charge has been found in association with minute solid particles, such as those which constitute a cloud of tobacco smoke. The smoke is blown into a glass vessel containing ionized air and powerfully illuminated from the side. Viewed under a microscope the particles appear as brilliant silver points, so that it is no longer necessary to treat the cloud as a whole but the actual displacements of individual particles can be followed. When an

electric field is applied, they separate instantly into three groups, one travelling with the field, therefore positively charged; one against it, negatively charged; and one which remains in place and is therefore neutral, consisting of those particles to which an equal number of ions of opposite signs have attached themselves. In this way Ehrenhaft has found the ionic charge to be 4.6×10^{-10} ; de Broglie 4.5×10^{-10} .

But a method devised by Townsend in 1900 admits of far greater accuracy. Without measuring the actual charge at all, he showed by comparing the coefficient of diffusion of ions with their 'mobility,' *i.e.* their velocity under the action of an electric field, that for all types of ions examined the charge carried must be the same as that carried by the atoms in electrolysis, with a possible error of less than one per cent.

The cumulative effect of all these instances, where the ions are produced in different gases, under different circumstances, by different means, but always are found to carry the same charge, forces the conviction that there exists an ultimate charge or 'atom' of electricity; that the particles of the cathode ray can be no exception; and that this atomic charge, or some very simple multiple of it, is the charge they carry, *not* a charge more than a thousand times as great. But if this be so then we are forced back on the other alternative, and the conclusion is irresistible

that in the kathode ray we are dealing with an entity a thousand times less than anything previously conceived by science. And since these particles are identical, whatever the gas from which they are derived, apparently they are a constituent of all matter. A modification of Prout's hypothesis is thus suggested. Prout held that the atoms of all other elements are built up of hydrogen atoms. It now appears that all atoms, that of hydrogen included, are at least partly constituted of particles of the same kind.

It is time to give a name to these new bodies. At first they were called corpuscles, but they are now known as *Electrons*. An electron, then, is a minute particle with an apparent mass about one-thousandth that of a hydrogen atom, and bearing a negative charge $e = 3.4 \times 10^{-10}$.

Canal Rays.

Meanwhile (1896) Goldstein observed a new type of ray within the vacuum tube. Employing a perforated kathode, he noticed cones of violet light projected from each of the holes *behind* the kathode. These rays he called 'Canal rays' from the passages in the kathode through which they issued. They were studied by Wien, by methods entirely similar to those just described.

Wien found that they could be deflected by magnetic and electric fields though much more feebly than the kathode rays, and the deflection was *in the opposite direction*. The value of $\frac{e}{m}$ was variable but never greater than 10^4 .

The canal rays must therefore consist of particles of atomic size and bearing a positive charge.

After a long interval their true nature has just been elucidated by some remarkable researches of J. J. Thomson (1910-12). He employs a kathode with a single long and very narrow perforation, leading to a large discharge tube. The particles projected through this passage are subjected to the action of an electric and a magnetic field mutually at right angles and both perpendicular to the path of the particles. Theoretically, the electric displacement should be proportional to the square of the magnetic displacement, and thus when the particles strike a screen placed to receive them, they should be found on the arc of a parabola. Thomson places a photographic plate within the discharge tube, and the plates, on developing, show in fact a number of such parabolic arcs, corresponding to as many different types of projected particles. The curves are measured and the latus rectum of each parabola gives the value of $\frac{e}{m}$ for the particles which formed it.

A discussion of the results reveals the presence of many types. Thus in an oxygen tube were found (1) ordinary molecules of oxygen each consisting of two atoms united ; neutral atoms ; atoms with single and double positive charges ; atoms with one negative charge ; molecules with one positive charge ; molecules of ozone (O_3) with one positive charge, and O_2 with one positive charge. Similarly with other gases. In mercury vapour some molecules carry as many as eight positive unit charges.

Negative charges are found associated only with atoms, never with molecules, and particularly with those of hydrogen and carbon. According to Thomson's conception of the atom, chemical combination and *valency* depend upon the presence of one or more free electrons, so that we get a hint of explanation of the peculiar chemical activity of gases in the 'nascent' state, *i.e.* at the moment of their formation, before the dissociated atoms have had time to unite into molecules, for it is only then that they can carry a negative charge.

By these researches a new method of chemical analysis has been opened up, far more sensitive even than the spectroscope. With only one-hundredth of a milligram of a gaseous element present in the tube, and an exposure of less than a millionth of a second, its atomic weight may be determined with an accuracy of one per cent. And not only is the nature of the

element disclosed, but its physical condition, whether atomic or molecular, charged or neutral. By this means too the greatest difficulty in the accurate fixing of atomic weights, the removal of impurities, is evaded. For impurities make no difference, since each curve corresponds to one and only one type of particle investigated.

Roentgen or 'X' Rays.

A third type of rays came to light in the late autumn of 1895. Roentgen, repeating Lenard's experiments, had covered the vacuum tube with a black paper case, so that the eyes might be more sensitive, in the complete darkness, for observing the effect of the kathode rays outside the tube. He thus noticed that whenever the tube was working, a fluorescent screen of barium-platinocyanide, which happened to be near it, lit up though no visible light could reach it. On placing the hand between the tube and the screen, to see whether the effect really came from the tube, he saw for the first time the shapes of the bones revealed through the enveloping flesh.

Though this discovery was in a sense accidental, the fame which it brought was fully deserved. Within a couple of months Roentgen worked out the consequences of his observation so completely that for a year or two after its publication hardly an extra fact

was elicited, though all the world precipitated itself on the research, and a sensation that would have been irresistible to a notoriety-hunter was modestly communicated in due course to the German scientific journals.

The main properties of the X, or unknown, rays as now established are these. They start from the place where a kathode ray strikes, from the walls of the tube in the first instance, or in a modern 'focus' tube from the piece of platinum upon which the kathode rays are converged. They issue *equally in all directions*; and travel in straight lines, for they cast shadows. Their power of penetration is not *selective*, as in the case of light, but depends only on the density of the substance penetrated. Hence the opacity of bone and comparative transparency of flesh. In spite of persistent effort no trace of the other familiar properties of light could be detected. The X-rays could be reflected, refracted, polarized, or made to show interference. On the other hand, they are not affected by the most powerful magnetic and electric fields, as the flights of charged particles constituting the kathode and canal rays would be. But they do share with kathode rays the power of exciting fluorescence, affecting a photographic plate, and making the air through which they pass *conductive*.

It was this latter property which gradually

engrossed the attention of scientific investigators, as the novelty of the photographs and shadow pictures of the bones, which had first struck the popular imagination, began to wear off. To account for it, J. J. Thomson and Rutherford brought forward the theory that the rays break up the neutral atoms of the gas into positive and negative carriers, or 'ions.' If the space between two plates connected to the positive and negative terminals of a battery is thus 'ionized,' the negative ions travel towards the positive plate, the positive ions towards the negative plate, and thus a current passes. But meanwhile the mutual attraction between the positive and negative charges of the ions tends to make them recombine into neutral atoms. The stronger the electric field applied by the battery, the faster the ions will move and the less time will they have for recombination before they reach the plates. The current will therefore increase as the potential difference of the battery is increased, but it will reach a limit when the strength of the battery is sufficient to carry all the ions to the plates before they have a chance of recombining. This limiting or 'saturation' current affords by far the most accurate and sensitive method of measuring the strength of any ionizing agent such as the X-rays. By its means, and by it alone, has it been possible to detect and discriminate the various radio-active products which

exist in quantities so minute as to be far beyond the reach of the chemical balance or even of the spectroscope. Some of them are so shortlived that their existence must be measured in minutes or even seconds; yet they can be identified with certainty by the ionising effects of their radiations.

In view of the important conclusions to be based on the theory of ionization it is reassuring to note that many workers, adopting very different methods, have arrived at consistent results concerning the properties of the ions. Their rate of recombination has been measured. Thus if there are a million ions present per cubic centimetre, one half of them will have recombined in less than one second, and 99 per cent. of them in 90 seconds. The speed of both positive and negative ions, in different gases at different temperatures, has been determined; their coefficient of diffusion; their approximate size; and the number produced per second in a cubic centimetre by various agencies. Ionization, it would seem, consists in removing an electron from a molecule of the gas. At ordinary pressures the electron at once becomes the nucleus of a cluster of neutral molecules, about thirty in number, the cluster forming a negative ion, through the negative charge of the electron. The rest of the molecule, still practically of molecular size, becomes positive, through loss of the negative charge of the electron. It forms the positive ion, and

is probably also the nucleus of a cluster of neutral molecules. The conclusion that at ordinary pressures the ions form clusters is deduced from their rates of diffusion. At low pressures they do not form clusters, the negative ion being simply an electron, the positive a particle of atomic size with a positive charge such as is found in the canal rays.

X-rays lack the characteristic properties of light on the one hand and of streams of charged particles on the other. What then are they? The view generally held was suggested by Stokes and worked out by J. J. Thomson. It is, that they are *pulses* in the ether originated by the sudden stoppage of an electron in its career. From the negative charge of the electron a Faraday tube of force must reach out through the ether, and it travels with the electron at its high speed, perhaps one-third the speed of light. When the electron is suddenly brought to rest, a jar or pulse travels out along the tube of force, as when a single jerk is given to the end of a stretched rope. Such a pulse would not show reflection, refraction or interference, for these are properties only of a *train of waves* with a regular period, though it might show a trace of polarization. Yet it is an electromagnetic disturbance of the ether in other respects like light. The more sudden the stoppage of the electron, the thinner will be the pulse, and the more intense the electric and magnetic forces

set up in it ; and these must be sufficient to separate an electron from a gas molecule, thus ionizing the gas. The theory explains why the X-rays originate at the point of impact of kathode rays ; and why they are not subject to deflection by an electric or magnetic field.

But though the 'pulse' theory of the X-rays at present holds the field, it is by no means yet firmly established. The question of their true nature remains one of the outstanding problems awaiting solution. Within the past few years Bragg has brought forward another view, adducing evidence which tends to show that they are *corpuscular* in nature, like the kathode rays, and not ether-disturbances at all. The movements of the ether which we know as light spread out in spheres, like all waves, so that as they recede from the source the intensity falls off according to the well-known law of inverse squares. Now it appears that in an X-ray the energy travels intact. In the picturesque phrase of Stark, who developed the theory from the work of Planck, an X-ray is 'a bundle of energy travelling without alteration of form.' But this is not necessarily inconsistent with the 'pulse' theory ; for if an X-ray is, according to Thomson, 'a kink in the *one* tube of force which characterises an electron,' the energy would follow the tube, instead of suffering diffusion like ordinary radiations from a source in all directions.

Other arguments are drawn from the scattering

of X-rays when they strike upon matter. When X-rays impinge on a thin plate, secondary rays issue from the plate on both sides but in greater numbers on the far side of the plate. These 'secondary' rays turn out to be of the nature of kathode rays, and are therefore corpuscular. Their speed does not depend on the material of the plate, *i.e.* on the kind of atoms of which it is composed, but does depend on the quality of the X-rays. So that it looks as if they were driven from the plate by the sheer impact of the X-ray, carrying forward, more or less, both its direction and its speed. From a survey of a large amount of work which has been done in recent years on the subject, Bragg concludes that

'One kathode ray impinging on an atom may produce one X-ray and no more, and in its turn the X-ray through impact on an atom produces one kathode ray and no more, handing on its energy and direction of motion.'

Such an action is characteristic rather of the impact of material particles than of wave-disturbances.

But if the X-ray is corpuscular, how shall we account for its extreme penetrating power and its immunity from the action of electric and magnetic fields? On the first count it cannot be gross matter even of atomic minuteness,—it must be electronic in size; and, on the second, it must be electrically neutral. Thus Bragg concludes 'I have myself found

it convenient to regard the X-ray as a negative electron to which has been added a quantity of positive electricity which neutralizes its charge, but adds little to its mass.'

And this is his theory of 'neutral pairs.' Against it must be set some researches of Barkla, who has shown that when X-rays of gradually increasing 'hardness,' or penetrating power, fall on a given element, suddenly a radiation appears, of the X-ray type, which is emitted equally in all directions and is slightly less penetrating than the rays which excite it. It differs in penetrating power for each element, the penetration usually increasing with the atomic weight of the element, and Barkla has found evidence of several types arising from the same substance, thus forming a characteristic 'spectrum' for the substance. This is analogous to the fluorescent spectrum emitted by certain substances when light falls on them, and suggests the phenomenon of resonance, as if atoms with one or more natural periods of vibration are only excited when the period of the incident radiation coincides with one of their own natural periods. Moreover Barkla has now found traces of polarization in X-rays reflected from material substances under proper conditions. These facts are consistent with the pulse theory, but hard to account for on any theory that the X-rays are corpuscular in character.

Thus, though to this day the true nature of the

X-rays remains an open question, already in 1896 the twenty years of study of the high vacuum tube had developed three types of radiation unknown before. The kathode ray had been shown to be a stream of negatively charged particles, minute compared with the smallest atom, but with a speed comparable to that of light itself. The canal rays were also streams of particles, but of atomic size, bearing a positive charge, and having a speed which though still considerable was decidedly less. The X-rays were believed to be not particles at all, but ether disturbances of the nature of light ; differing however from a light ray as a single clash differs from the organised train of waves with a regular period which constitutes a musical note.

CHAPTER III

THE NEW RAYS

To produce X-rays with a vacuum tube electrical energy must be supplied, and then the walls of the tube where the rays originate fluoresce brilliantly. It was natural to suppose that the fluorescence was the cause of the rays, and the conservation of energy seemed to demand that they could only be maintained

so long as energy in some form was supplied. Both these clues turned out to be false, and yet they led to a real discovery.

Many substances were known to fluoresce when excited by the energy of sunlight. Accordingly several investigators—Niewenglowski, H. Becquerel, Troost, Arnold—exposed fluorescent substances such as calcium sulphide and hexagonal blende to sunlight and found that they gave out rays which could affect a photographic plate through black paper. Le Bon obtained results in this way which he attributed to ‘dark light.’ But all these effects are now known to be due to ultra-violet rays capable, in virtue of their very short wave-lengths, of penetrating substances opaque to ordinary light.

It was with uranium, well known for its beautiful fluorescence, that the first discovery in radio-activity was made, by Henri Becquerel in February 1896. He found that the double sulphate of uranium and potassium exposed to sunlight could affect a protected photographic plate. The effect could not be due to ultra-violet light, for the rays penetrated thin sheets of metal and glass, which also excluded the possibility of chemical action due to vapours emitted by the salt. Further investigation showed that fluorescence had nothing to do with it. The uranic salts are fluorescent while the uranous salts are not. Yet both proved to be active *in proportion to the amount of uranium*

they contained. Nor was the energy of sunlight needed. Salts which had been kept in the dark for years were as active in the dark as when exposed to sunlight. Even crystals which had been deposited in the dark, without ever being exposed to light, showed the same activity.

The continuous emission of these penetrating rays is thus a specific property of the element uranium itself. It does not depend on the supply of external energy. Nor can the rate of emission be altered by any known physical or chemical process. Lapse of time and extremes of temperature, from that of liquid air upwards, fail to diminish it. Exposure to ultra-violet light or X-rays does not increase it. This was an altogether novel property, and an exhaustive search was at once begun to see if any other known element possessed it.

It was soon found, by Schmidt and Mme Curie, that thorium was active. Mme Curie then examined the minerals containing uranium and thorium by the electric method, *i.e.* by their power of ionizing the air between two electrified plates. A striking result followed. Some of the minerals, pitchblendes from the Austrian mines, were about *four times as active as uranium itself*. Chalcocite, a crystallized phosphate of copper and uranium, was twice as active as uranium, whereas, when the salt was prepared artificially from pure materials, it showed its proper

activity, according to the proportion of uranium contained, *i.e.* two-fifths of the activity of uranium. The natural mineral was thus five times as active as the artificial, a result that could only be explained by the existence of some impurity far more active than uranium itself.

The Austrian Government presented M. and Mme Curie with a ton of uranium residues from the State manufactory at Joachimsthal, and there ensued a long and laborious search for the suspected trace of impurity. Endless precipitations and fractional crystallizations were employed, the active agent being unerringly tracked down by testing the activity of the precipitates and residual solutions at every stage, until the patient ingenuity of the investigators was rewarded by the separation of a few milligrams¹ of two active bodies to which Mme Curie gave the names polonium and radium, the first in honour of her native country, the second, by a happy inspiration, on account of its extraordinary power of radiation, more than a million times that of uranium.

The radium was obtained in the form of a chloride. All there was to show for months of labour on a ton of materials was a minute pinch of white powder, at present worth £15 a milligram or about £1000 a

¹ From a ton of pitchblende may be extracted 200 milligrams of radium chloride, and one five-thousandth as much polonium, *i.e.* one twenty-fifth of a milligram.

grain. But its properties amply repaid the toil. Its radiations light up a fluorescent screen brilliantly, blacken a photographic plate, and instantly ionize the air in its neighbourhood. A few milligrams carried in the pocket will soon produce a deep abscess in the side, as M. Becquerel found when he brought some from Paris to London for a lecture at the Royal Institution.

Since radium is very closely allied to barium in its chemical properties—this had been one of the chief difficulties in its separation—it was important to make sure that a new element had been discovered, not merely a modified form of barium. This was established when it was found to give a new and characteristic spectrum. Its atomic weight has been determined as 226. It is thus the heaviest known element except uranium. Recently (1911) Mme Curie has at last obtained the pure metal.

The brilliant researches of the Curies impelled many others to investigate the pitchblende residues. Several active bodies were separated and named actinium, radio-tellurium, radio-active lead. Subsequent research has shown that, with the exception of actinium, these substances and also the polonium first discovered by Mme Curie must be referred to the radium family itself, so that the only elements at present known to be radio-active are uranium, radium, thorium, actinium. We shall see that the

first two are members of the same family, while more than a score of new active substances, derived from uranium, thorium and actinium, have been detected.

What was the nature of these new radiations? Their fluorescent, photographic and ionizing properties could not discriminate them from kathode rays, X-rays, or ultra-violet light, all of which produce similar effects. But each of these properties could be used as a means of measuring their intensity. In this way a further study was made first of their powers of penetration, and then of their susceptibility to the action of magnetic and electric fields.

It was found at once that the new radiations were not homogeneous. A sheet or two of paper, one or two layers of thin aluminium foil, or even a few centimetres of air, cut off a large part of the effect. There remained a second type of radiation which could only be stopped by a thickness of one-eighth to one quarter of an inch of solid lead. And even then there was a residue which could be detected after passing through six inches of lead or several feet of iron.

These three types of radiation were named by Rutherford the α , β , and γ rays respectively. There are differences in penetrating power among the rays of any one class according to the source. Thus a range of about one 'octave' in penetrating power is found among α rays, *i.e.* some α rays are about twice

as penetrating as the least penetrating α rays. But there is a sharp distinction between the classes. Roughly speaking the penetrating powers of the three types are in the proportion 1 to 100 to 10,000, β rays being 100 times as penetrating as α rays, and γ rays again 100 times as penetrating as β rays.

When an electric and a magnetic field were applied, it was easily found that the β rays could be deflected, but the α rays gave much more trouble. Rutherford at last succeeded, and as an indication of the difficulties to be met with in these experimental investigations, his arrangement is worth notice.

To increase the effect, 20 to 25 slits between brass plates from $\frac{1}{25}$ to $\frac{1}{80}$ of an inch apart were employed. These were placed beneath the electroscope with a thin layer of radium below them. The electroscope was charged and the rate at which the gold leaf B fell back to the plate D was observed through a mica window by means of a microscope with a micrometer eyepiece. This gave the rate at which the air in the electroscope was ionized by the rays passing up through the slits. It will be seen later that radium gives off a radio-active gas. To prevent this leaking up through the slits an aluminium foil was waxed down above them and a current of hydrogen was kept flowing down through the porous foil. The most powerful magnetic field available was then applied so as to deflect the rays towards the walls

of the slits. The α -rays could be cut off by covering the radium with a sheet of mica, which allowed the β and γ rays to pass. The ionization could thus be observed (1) with or without the α rays, (2) with or without the magnetic field. The results showed that

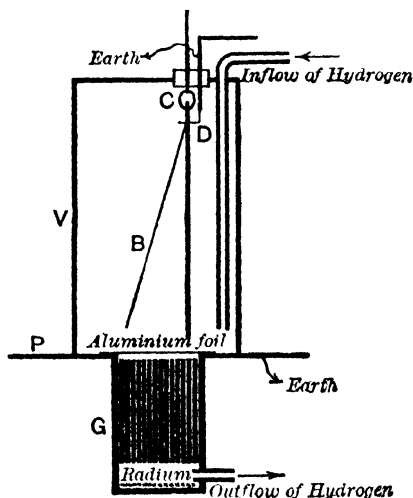


Fig. 2.

the α rays were deflected. By covering half the top of each slit by a brass ledge projecting from one side it was possible to detect the *direction* of the deviation. Later on the rays were received on a photographic plate and the *amount* of deflection measured. The way was thus open to apply to the α and β rays the

same methods by which the velocity and ratio of charge to mass had been determined for the kathode and canal rays.

The general results obtained were as follows.

The α rays bear a positive charge and the particles of which they consist have a speed about one-tenth the velocity of light. The ratio of charge to mass is about *half* that of the hydrogen atom in electrolysis. Though deviable by magnetic and electric fields, the amount of deviation is minute compared with that of kathode rays or β rays. They thus correspond to the particles of the canal rays in the vacuum tube, being of atomic size—about twice the mass of the hydrogen atom.

The β rays consist of particles with a negative charge. The ratio $\frac{e}{m}$ is 10^7 , the same as in the kathode rays. The velocity ranges from about two-fifths up to nine-tenths the velocity of light itself. The particles of the β rays are thus identical with those of the kathode ray, being about one-thousandth of the mass of the hydrogen atom. They are in fact electrons, but with an enormously greater speed than those projected in the vacuum tube.

The γ rays cannot be deflected by magnetic or electric fields. They resemble in all respects the X-rays, but are far more penetrating than X-rays from the 'hardest' vacuum tube. They are probably

of the same nature, *i.e.* not particles at all, but thin pulses in the ether.

It thus appears that certain of the heaviest elements, uranium, radium, thorium, are continuously projecting, unaided, without any supply of external energy, three types of radiation strictly analogous to the three types which may be produced from a vacuum tube driven by a powerful induction coil. They may justly be called 'radio-active' elements.

The fact that the α particles carry a positive and the β particles a negative charge has been deduced above from the direction in which they are deflected by a magnetic field. This has been proved directly, though the experimental difficulties were great. This chapter may fitly be closed with a reference to Strutt's 'radium clock,' at once a demonstration and an ingenious application of the fact.

An active preparation of thirty milligrams of radium bromide are ~~are~~

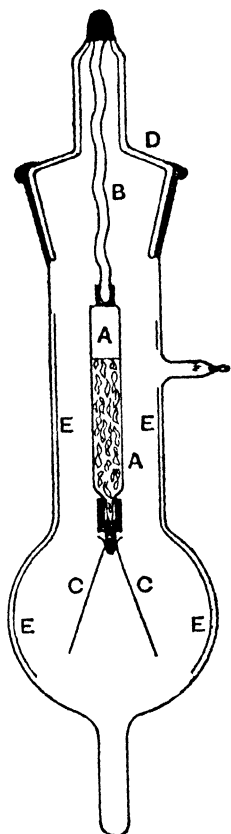


Fig. 3.

sealed into a thin glass tube *A*, which is supported on an insulating quartz rod *B* within an exhausted outer tube *D*. The walls of *A* are made conducting by a thin coating of phosphoric acid. From the lower end of *A* two gold leaves *CC* are suspended, in metallic connection with the radium in *A*.

The walls of *A* absorb all the α particles discharged from the radium, but allow the β particles to escape to the outer tube. The radium and the leaves attached to the tube thus acquire a positive charge and the leaves steadily diverge. When they come in contact with strips of tin foil *EE*, connected with the earth, the leaves are discharged and collapse, only to begin at once the same process over again. This operation is repeated about once a minute, and from what is now known it would still be in progress, though only half as quickly, after the lapse of two thousand years. This is the nearest approach to perpetual motion hitherto attained.

CHAPTER IV

THE NEW SUBSTANCES

URANIUM and thorium, in view of their strange property of radio-activity, were naturally subjected to much investigation. In the early days of this

research some puzzling and indeed at the time inexplicable facts came to light.

For instance, all the evidence pointed to the conclusion that radio-activity was a specific property of the *atom* of uranium or thorium. The activity of any salt was proportional simply to the amount of element it contained, and depended in no way on its state of chemical combination. No known chemical or physical agency was able to affect the rate at which the process went on. In 1900, however, Crookes precipitated a uranium solution with ammonium carbonate, dissolved the precipitate in excess of the carbonate, and finding that a light precipitate remained, filtered it out. This residue, though chemically free from uranium, proved to be several hundred times as active as uranium *when tested photographically*, while the uranium solution had lost the power of acting on a photographic plate.

Rutherford and Soddy then attacked thorium, and by precipitating it with ammonia obtained a residue several thousand times as active as thorium, though chemically free from it. The precipitated thorium was found to have lost more than half its activity.

The active substances thus separated were called, from their 'unknown' nature, Uranium X and Thorium X. That they were new substances with distinct chemical properties seemed clear from the

way in which they had been obtained as the result of specific chemical processes. For the ammonium carbonate, which separated uranium X, fails with thorium; and ammonia, which was at the time the only agent capable of completely precipitating thorium X, fails to separate uranium X¹. Thus new substances had been separated from uranium and thorium possessing the property which seemed to belong to the *atoms* of those elements, and leaving the latter partially or wholly inert.

A still more remarkable fact was to follow. Becquerel set aside an active solution of Ur X and the uranium from which it had been obtained. On examining them at the end of a year he found that *the uranium solution had regained its activity, while that of the Ur X had disappeared*. The same was true for thorium solutions. Rutherford and Soddy found that at the end of a month *the thorium X was no longer active, while the thorium had regained its activity*. Obviously the next step was to trace in detail the laws of decay and recovery with lapse of time. Rutherford and Soddy did this in a long series of measurements for thorium and then for uranium.

¹ Several other agents are now known to be capable of precipitating thorium X, but the success of Crookes' experiment with ammonium chloride has been found to depend on the presence of a trace of impurity! So that uranium and Ur X are the Dr Jekyll and Mr Hyde of the subject! One way is to add a trace of iron—ferric hydroxide—to the pure salt.

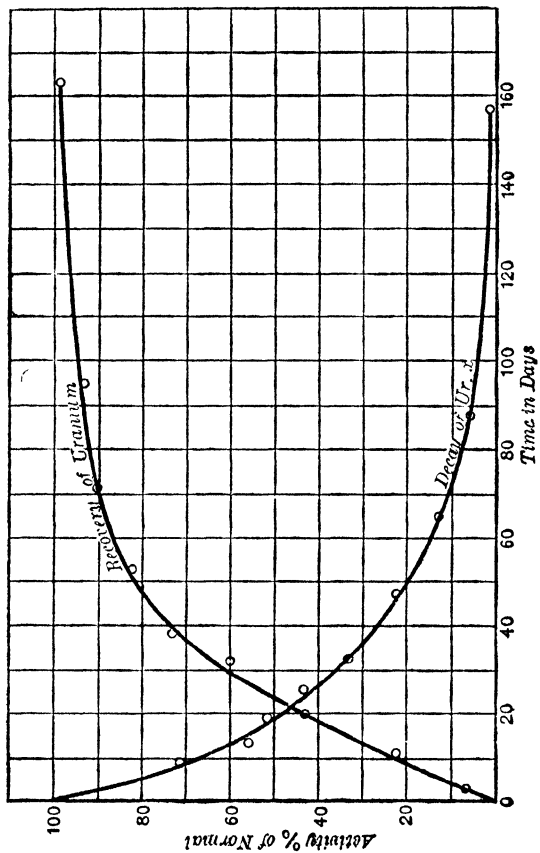


Fig. 4.

Fig. 4 shows the results for uranium and Ur X plotted in curves.

Consider first the curve of decay of U· X. It is a curve well known to mathematicians as an *exponential* or *logarithmic* curve. It indicates a law frequently met with, viz. that the quantity changing at any instant is a fixed fraction of the total amount existing at that moment. When, for instance, a *monomolecular* chemical change is taking place, i.e. a change in which only one kind of matter is involved, it is according to this law that it proceeds. Of all the unchanged molecules existing at the beginning of any second a fixed proportion will effect the change during that second. The change therefore begins fast, proceeds more and more slowly as time elapses, and theoretically should never reach completion. The swings of a pendulum left to itself die away according to this law. The energy taken out of the pendulum by frictional resistances during each swing must be proportional to the length of the swing during which they can act. Hence each swing is less than the last by a fixed fraction *of the last*. This, too, is the law of decay of an electric current in an inductive circuit when the source of power is suddenly cut off. The processes of radio-activity cannot be understood unless this principle is grasped. Therefore a more familiar illustration may be given. If the decay curve is taken in the reverse direction, beginning

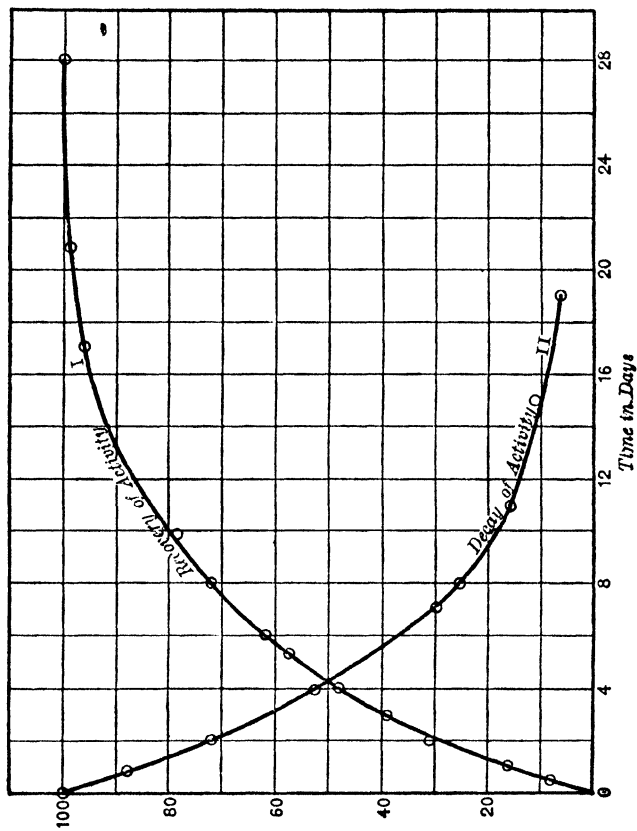


Fig. 5.

I. Thorium.

II. Thorium X.

with the small value in the right-hand bottom corner, it represents the growth of a sum of money invested at compound interest; for the rate of increase at any moment is a fixed percentage of the amount existing at that moment.

All logarithmic curves are of the same type and are expressed by a mathematical equation of the same form. They only differ in the *rate* at which decay takes place. This is most conveniently measured by the time taken for the original amount *to fall to half its value*. The moment this is known, the whole curve can be drawn. In the case of uranium X it is about 22 days. For thorium X (fig. 5) it is about 4 days. Otherwise, as the figures show, the curves are precisely similar.

Turning now to the recovery curve, we see that it is nothing but the decay curve *upside down*. It rises rapidly at first, then more and more slowly, approaching the normal value of 100, but never reaching it, precisely as the decay curve approaches zero. The growth in any second is a *fixed fraction of what still remains to be accomplished*. And here a very important point must be noted. The sum of the values for the two curves at any one instant is, if the curves are accurately drawn, exactly 100, and equal to the original amount. This is only approximately true in the figures given, which represent actual experiments liable to slight errors. The two

curves are in fact *complementary*, the total activity existing in the uranium X and the uranium being precisely the same throughout the process. As the Ur X loses its activity, step by step the uranium regains what the other loses, as if by direct transfer between them. This is found experimentally to be the fact, whether the two solutions are kept near each other, or separated to great distances, or enclosed in lead which would prevent any possible direct radiation. Nor can any known agency affect the rate of the process. Extremes of temperature, light and darkness, vacuum and high pressure, violent chemical reagents and electric forces have all been tried, but the decay and recovery go irresistibly on.

Strange as these facts appeared at the time, they admit of a simple explanation. But before it was hit upon, two similar phenomena had been discovered.

The Emanations.

Workers with thorium had been much troubled by unaccountable irregularities in their measurements of radiation. When an open testing vessel was used, a slight current of air, or the mere opening of a door at the other end of the room, would cause great differences in the readings of the electrometer. On investigation Rutherford concluded that a minute trace of some active substance was given off by thorium, which could be blown about from place

to place. Whether this was a vapour, or perhaps a fine dust, such as that to which the odour of musk and some metals is due, or, may be, even a new gas, was doubtful. In order not to prejudge the question Rutherford happily called it the 'emanation.' It was soon found to possess many of the properties of an active gas. It diffused through paper and thin metal foil, but not through mica or glass. It could be carried by a current of air through tightly packed cotton wool, and bubbled through solutions without losing its activity. When a quantity of the emanation was left to itself, however, its activity decayed by an exponential law, just as the action of ^{radio}Ur X and Th X do, only much more rapidly. The activity of the thorium emanation decays to half value in about one minute. On the other hand, the activity of the emanation due to a thorium compound placed in a closed vessel rises to a maximum, reaching half value in about one minute. The two curves are complementary, exactly as in the case of uranium and uranium X.

When radium was examined it was also found to give out an emanation which behaved in the same way except that it had a longer life. The activity of the radium emanation, left to itself, decays to half value in a little less than four days, about 5000 times the time taken by the thorium emanation.

Evidence accumulated that these emanations were

new gases of high atomic weight akin to the argon family. They behaved like ordinary gases in diffusion experiments, and their coefficients of diffusion indicated high atomic weight. They passed unscathed through a platinum tube heated electrically to the highest possible temperature and filled with platinum black; through red hot lead chromate, magnesium powder, zinc-dust, reagents which would have affected any known substances except the heavy gases of the argon family.

But the real proof of their gaseous nature was only effected when Rutherford and Soddy succeeded in condensing them by means of low temperatures. A liquid-air machine was specially obtained for this experiment, and the writer well remembers how with the first litre of liquid air produced the condensation was successfully brought about. The emanation was conveyed to the testing vessel by a slow stream of hydrogen passing on its way through a spiral which could be immersed in liquid air. So long as the spiral was immersed, no trace of activity was seen at the electrometer. But if the liquid air was removed and the spiral allowed to warm up, at a temperature about 154° C. below zero the needle of the electrometer suddenly moved through several hundred divisions, showing that the accumulated emanation which had been condensed during immersion had been set free.

The emanating power of the various compounds of thorium and radium, *i.e.* the rate at which they give off emanation, depends much on chemical and physical circumstances. Thus thorium nitrate in solution gives off 600 to 800 times as much as in the solid state. But Rutherford and Soddy have shown that these differences are due to the occlusion of the gas in the solid. The rate of *production* is independent of circumstances. They also proved that the origin of the thorium emanation is *not thorium, but thorium X*. When Th X is separated from a thorium solution, the Th X has marked emanating power, while the precipitated thorium hydroxide shows scarcely a trace. But now the Th X begins to lose its emanating power, while the hydroxide regains it; and if the curves are plotted, they prove to be *identical* with the curves of decay and recovery of *activity* for Th X and the thorium hydroxide. *The active radiation of Th X thus accompanies the emission of the emanation from it.*

Throughout the elaborate researches summarized in this chapter the only guide has been the *activity* of the substances concerned, measured either photographically or by the electric method. The quantities obtained are too small to be detected otherwise. Ur X and Th X are mainly impurities associated with uranium and thorium, containing an infinitesimal trace of the active constituent. So, too, with the

emanations. The amount of thorium emanation is too small and it decays too rapidly ever to be detected by its volume. The rate of production of emanation by radium is about a million times greater, and it has a longer life. Nevertheless the emanation from one gram of radium is less than one cubic millimetre. Yet Ramsay and Soddy by extraordinarily skilful experiment, with only 60 milligrams of radium at their disposal, not only detected and measured the volume, but proved that the minute bubble of gas obeyed Boyle's law, and showed that its volume, when left to itself, decreased according to the same law by which the activity of the emanation was known to decay. It is now known that even of this bubble only 5 per cent. was pure emanation. The first accurate measurement was made by Rutherford, who purified the emanation and obtained only one-twentieth of the amount found by Ramsay and Soddy.

The Active Deposits.

It was discovered (by M. and Mme Curie for radium and by Rutherford for thorium) that solids which have come in contact with the emanations become themselves radio-active. They behave as if active matter had been deposited upon them from the emanations.

This effect is due not to the radiations, but to actual contact with the emanations, as was proved by Rutherford, from an experiment due to P. Curie.

A solution of a radium salt is placed inside a closed vessel within which various plates *A*, *B*, *C*, *D*, *E* (fig. 6) are disposed, some protected from direct radiation by heavy lead plates, as *D*, others like *E*, directly exposed.

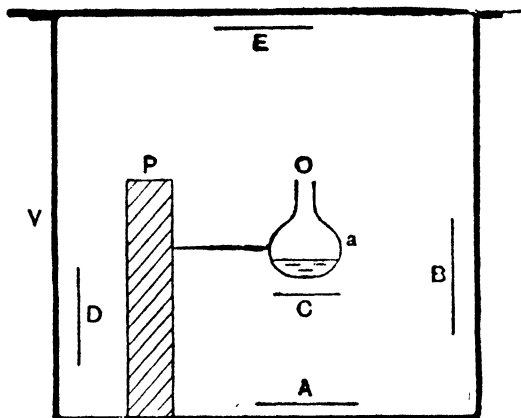


Fig. 6.

All become radio-active, the intensity being independent of the position or material of the plates, and proportional simply to their area. If the solution is covered with a few sheets of paper, which cut off the α rays but allow the emanation to diffuse through, the plates become active. If a sheet of mica is waxed

down over the solution, thus stopping the emanation, no activity is produced. Uranium and polonium, which do not produce an emanation, do not render the plates active. If one of the plates is connected to the *negative* terminal of a battery or electric machine, the whole of the activity will be concentrated on that plate.

In this way a short thin platinum wire, negatively charged and exposed to the thorium emanation, may be made more than 10,000 times as active as the thorium from which it was derived.

The active deposit may be rubbed off the wire or plate by sand paper, but then it is found on the paper. It can be driven off by electrically heating the wire, but is then found on the interior of the vessel in which the wire is heated, as if it had been sublimed. It has definite chemical properties; for it will not dissolve in water or nitric acid, but is soluble in sulphuric and hydrochloric acids. When the acid solutions are evaporated, the activity remains on the dish.

It is thus clear that the emanations give rise to a solid active deposit of definite chemical character. But the amount must be infinitesimal; for not the slightest difference in weight can be detected, nor can anything be seen on the active wire under the most powerful microscope.

When a wire which has been exposed for a *long*

time to thorium emanation is left to itself, its activity decays in the now familiar way by an exponential law, the characteristic time of falling to half value being about 11 hours. As we are now prepared to

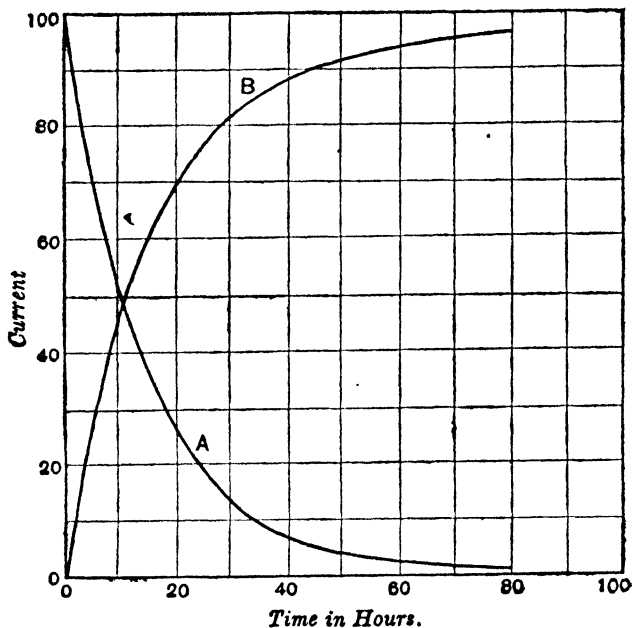


Fig. 7.

expect, the curve showing the rise of activity in the wire during exposure to the emanation is the complementary curve. The two are shown in fig. 7.

We have now traced the discovery and the laws of

production and decay of the following new substances, new because absolutely unsuspected by chemists before their existence was revealed by their radioactive properties :

Uranium X.

Thorium X—The Emanation—Active Deposit.

Radium Emanation—Active Deposit.

Uranium X produces no emanation. On the other hand radium gives rise directly to the radium emanation, without the intervention of anything corresponding to uranium X and thorium X. Thorium alone gives the complete series,

Thorium—Th X—The Emanation—Active Deposit, each member of which seems to be the parent of the next.

This was the stage at the end of 1904. We shall see that a great development has taken place since.

CHAPTER V

DISINTEGRATION

THE complicated facts detailed in the last two chapters, together with many others too numerous to be included within the limits of this essay, have received a beautifully simple explanation, now to be

described, which links them all together, each in its natural place, as parts of a single theory. Yet this theory ran so counter to received ideas that it was not without conflict it attained its present universal acceptance.

Two main facts had to be explained. First, the production from apparently inert matter of the new radiations, representing a very large output of energy compared with the weight of the substances from which it was emitted. And next, the simultaneous production, proceeding step by step with the radiations, of a whole series of new substances with distinctive chemical properties, themselves radio-active, with an activity, however, which decayed according to characteristic laws.

Looking back from our present point of vantage, it is hard to realize the confusion introduced by the new facts among the ideas current ten years ago, and the apparent shock to the principles then accepted as established. The century-long belief in an unchangeable indestructible atom forbade anything more than a chemical reaction between *elements*; confidence in the conservation of energy compelled a search for the source of the energy expelled, which enormously exceeded, weight for weight, the energy disengaged in the most powerful chemical reaction known, that between oxygen and hydrogen. Small wonder that the investigators cast about rather wildly for an idea

that would fit the facts. The Curies suggested that the emanation was not material, but consisted of 'centres of condensation of energy attached to the gas molecules'; that the radio-active particles had the power of abstracting energy from the surrounding air, contrary to Carnot's principle; or again, that they obtained it by absorbing Roentgen rays passing through the atmosphere. Kelvin, as late as 1903, suggested that radium could absorb some unknown radiations. Crookes held that the energy was abstracted from the gas, the radio-active particles receiving the impact of a gas molecule and sending it out with a lowered velocity.

The theory which has cleared away all difficulties is known as the Disintegration Theory. It was brought forward by Rutherford and Soddy in 1902, for thorium, and in 1903 for radium and radio-active change in general. It consists of two parts: first, an interpretation of fact, as revealed by the curves of production and decay of activity of the new substances: and next a suggestion, as bold as it is simple, of the physical mechanism involved in the changes.

Interpretation of the Curves.

Consider the two complementary curves which express the growth and decay of activity in any of the cases described in the last chapter, for instance,

those for uranium and Ur X (fig. 4). These curves indicate

(1) that uranium produces an active substance Ur X at a constant rate, unalterable by any known process ;

(2) that Ur X loses its activity according to an exponential law.

The activity of uranium which has been left to itself for a long time is thus due to an *equilibrium* between the constant production of fresh Ur X, and the gradual loss of activity of the Ur X already existing.

When the Ur X is separated from the uranium, it at once begins to lose its activity according to the decay curve. Meanwhile the uranium goes on producing fresh Ur X at the same rate, and thus begins to regain its activity. The fresh Ur X loses its activity, like that already separated, but the constant production of new Ur X increases the activity of the uranium solution till so much has been produced that the fractional loss of activity of the new Ur X is again just equal to the activity of the new Ur X produced per second. Equilibrium is thus again established and the uranium is found to have regained its normal activity.

One feature of the complementary curves is at once explained. Since the rate of loss of activity of the Ur X is unaltered by separation, and the new

Ur X falls off at the same rate as if separated, the result would be the same if the two solutions were kept together, and the *total activity is unchanged throughout*. Hence, as is found from the curves to be the case, the *sum of the activities for the two curves is always the same, and equal to the normal activity*.

The importance of this principle justifies a familiar illustration. Let us suppose a man falls heir to an estate from which £100 a month is paid into his account, and resolves to spend each month one tenth of all he has in the bank. His account for the first year will run as follows :

Months	In Bank	Spends	Balance
1	100	10	90
2	190	19	171
3	271	27	234
4	334	33	301
5	401	40	361
6	461	46	415
7	515	51	464
8	564	56	508
9	608	61	547
10	647	65	582
11	682	68	614
12	714	71	643

The reader is advised to plot these numbers on squared paper, and continue them further. He will obtain the curve of growth of fig. 4. It is clear

that the amount in bank increases fast at first, then more slowly, and tends at last to reach £1000, though it never actually attains that sum. If it were attained there would be *equilibrium*. For then £100 would be spent each month, and this would be replaced exactly by the £100 regularly paid in.

It will be noted that the increase in the amount in bank at the beginning of each month is *one-tenth of what remains to be gained in order to reach the £1000*. Thus in the first month £900 is required and the increase is £90. This was pointed out as a property of the curve of growth.

If, now, after a year or two, when the normal £1000 has practically been attained, the trustees are temporarily unable to continue their payments, and the man starting with his £1000 goes on living by the same rule, he will spend £100 the first month, £90 the second, £81 the third and so on. *His capital will fall off according to the decay curve and approach zero.*

But should the trustees, foreseeing that their difficulty is only a temporary one, authorize him to count on the ultimate reception of the £100 a month, his expenditure, *i.e.* the *total activity*, would remain at £100, being drawn less and less from the £1000 in hand, and more and more from the accumulating hundreds not immediately available. By the time he would have exhausted his £1000, the normal

£1000 would just be re-established in his bank account.

The Physical Mechanism.

Up to this point there is nothing hypothetical. We have merely interpreted the meaning of the curves and learned from them the facts as to the production of the new substances. It remains to guess the physical process which underlies these changes; and it must be one which will at the same time account for the emission of the radiations and the enormous output of energy which accompanies them.

The daring suggestion put forward by Rutherford and Soddy was that in every second a certain percentage of the existing atoms of uranium *break up* or *disintegrate*, each atom throwing out an *a* particle with great velocity. The mass of an *a* particle, from the value of its ratio $\frac{e}{m}$, appeared to be twice that of a hydrogen atom; but there was evidence indicating, what has since been proved, that the *a* particle is really an atom of helium, with four times the mass of a hydrogen atom, only carrying a double charge, which would give the same value for $\frac{e}{m}$. The atomic weight of uranium is 238. On the expulsion of the *a* particle 4, the residue would be an atom 234^1 compared

It has been found since that uranium emits *two* *a* particles, so that the atom of Ur X is 230. See Table p. 91.

with hydrogen, and this *residue is an atom of uranium X*. The new atom is itself unstable, and every second a certain percentage of those existing will in turn break up, ejecting in this case a β and a γ ray. Since the γ ray is not material, and the β ray is only an electron, the residue is still an atom of Ur X, but lacking an electron. For uranium the next stage could not then be traced.

Why then, the reader may ask, does uranium lose its activity on the separation of Ur X, though it goes on producing Ur X at the same rate, ejecting an α particle for every atom formed? This is because Crookes used the photographic method in testing the activity, and the α rays of uranium have very little photographic effect, which is due almost entirely to the β rays. On the other hand, the α rays do most of the ionizing, and had he used the electrical method, he would not have found the activity of the uranium much diminished.

Two other points should be noted: in any series of radio-active changes the β rays do not in general appear until the last that can be traced, or at all events the last preceding either a *rayless*, or on other grounds presumably less violent change. For example, the last products of the Thorium and Actinium series break up with such violent explosions, and Radium C, the last of the rapid changes in the radium series, ends with one. The β particles are shot out with astounding

violence, having a speed often closely approaching that of light itself. Those from radium *C* attain .998 of the speed of light. The cause of the disruption of an atom is not known, but it looks as if the β particle is the disturber, and once it is got rid of comparative peace is restored, though several α particles may be thrown out before this can be brought about.

The γ ray *only and always accompanies* the β ray. This is what should be expected, if γ rays are pulses in the ether generated by the stoppage, and therefore also by the sudden starting of a β particle.

The changes that take place in thorium and radium are far more complicated than in the case of uranium; but a vast amount of patient experimenting has succeeded in elucidating them. We will only note here the first few steps disclosed.

Thorium emits an α particle at each of the changes from thorium to thorium X, from thorium X to the emanation, and from the emanation to the active deposit. The active deposit gives out all three types of radiation, α , β and γ rays. Radium gives out α particles on changing to the emanation, and again when the emanation passes into the active deposit. The deposit gives all three types.

The theory thus explains why the transformations are accompanied, step by step, by the radiations. It also suggests the source of the energy developed.

It must be withdrawn from the internal energy of the atom. The atom is to be conceived as a complex planetary system in which negative electrons and positive α particles, or some other form of positive electricity, revolve about each other with enormous speed. For some as yet unknown reason some of the atoms of the radio-active elements from time to time become unstable, ejecting an α particle with its orbital velocity, just as a stone leaves a sling, or the parts of a fly wheel are projected, if the speed becomes too great for the strength of the spokes.

With a natural reluctance to admit the possibility of change in an atom, it has been suggested that radium is but a chemical combination of helium and the emanation ; and so for the other cases of radio-active change. But the reasons which compel us to regard radio-active changes as *atomic*, not *molecular*, are too strong. The spectra of radium, the emanation, helium are absolutely distinct and characteristic, as of new elements, instead of being related as they should be for a compound and its components. The energy released is more than a million times greater than in the most intense chemical reaction known between molecules. Chemical reactions are greatly influenced by heat and other physical agents such as electric force. But radio-active changes cannot be accelerated or retarded by any known physical agency. This would be strange if they were reactions

between molecules as in chemistry. But it is just what would be expected if they are changes in the atom, for the very name *element* indicates that the forces employed in ordinary chemistry have failed to produce any further effect. Finally, no known chemical reaction gives rise to the radiations that accompany radio-active change.

It is not surprising that this theory met with opposition. The wonder is that so profound a revolution in ideas should have been effected within a single decade. The unchangeable atom is seen in the act of dissolution. The alchemist's dream of transmutation of the elements is in spontaneous operation from day to day. Not, indeed, between the nobler and baser metals, nor is the process subject to the experimenter's control. 'Il n'y a pas' says Mme Curie in her recent monumental work on Radio-activity (1911) 'encore actuellement de raisons suffisantes pour admettre que la formation de certains éléments puisse être provoquée à volonté en présence de corps radio-actifs. La production d'hélium reste acquise ; mais elle est reliée à une propriété essentielle des éléments radio-actifs et n'est pas influencée par l'intervention de l'experimentateur.'

The reason why the new views made way so readily is that the ground was already prepared. It often happens that a step in scientific discovery must wait a century or so after its first prevision

before it can be taken, because progress in some other part of the field lags behind the general advance. But in the case of radio-activity all was ready. The three types of radiation emitted by the radio-active elements had been elucidated by the study of the vacuum tube. Thomson had demolished the solid unchangeable atom and discovered the electron. The X rays had brought about the ionization theory of the conduction of electricity through gases, on which the best method of making measurements in radio-activity is based. It was a singularly fortunate coincidence that the leading ideas required for both theory and measurement should be thus to hand. As early as 1900 Mme Curie, in her thesis for the doctorate, had spoken of 'transformations not ordinary but atomic,' of the violent interior movement in the atoms, which she described as unstable, '*en train de se disloquer*,' and radiating particles less than an atom, while the sub-atoms were in movement. But it was in 1902 that Rutherford and Soddy first gave the theory a definite form and showed in detail its aptitude for explaining the facts known in the case of thorium.

CHAPTER VI

A FAMILY TREE

RADIO-ACTIVE change is by no means complete when the active deposit is reached. To disentangle the complicated subsequent changes has been the object of a vast amount of ingenuity and patient labour. It is marvellous that so much has been accomplished when the total quantity of matter available for work was far too small to be detected by the balance, the microscope, or the spectroscope. In default of the usual means employed by the chemist, investigators had at their disposal the three methods of studying the radiations, by their photographic, fluorescent and, above all, their ionizing effects. When radiation fails, the further transformations, if they exist, pass out of our ken. As a type of this work let us consider what has been discovered of the radium family.

Radium, as we have seen, does not produce Radium X, but with the emission of an α particle yields the emanation direct. With a solid salt of radium the emanation is mostly occluded in the salt. But it is disengaged on solution. Accordingly a radium solution is placed in a flask, and a platinum

wire, maintained negative, is inserted through a rubber cork. The emanation decays to half value in about four days, and forms the active deposit on the wire, again with the emission of an α particle.

The wire can be removed at any stage, and its activity studied. It is found that the greater part of this activity disappears within 24 hours; but a very small part, less than one hundred thousandth of the whole, remains and goes through a much slower series of changes.

Take first the activity of rapid change. The curves of decay obtained are quite different according as it is (1) tested by the α , or the β and γ rays (the latter give identical curves, since the γ ray always accompanies the β ray); and (2), exposed for a long or a short time to the emanation before it is examined.

Figure 8 shows the curves for the α rays. Both curves exhibit three well-marked stages. The first and the last stages follow an exponential law, the times of decay to half value being about 3 minutes and 28 minutes respectively. The middle stage is not exponential, but indicates a conflict between a substance decaying exponentially, and fresh production of that substance, not however at a constant rate. When mathematical equations are applied to these curves, it is found that they can be completely explained by assuming three successive changes:

- (1) The emanation produces a substance (radium

A) which decays rapidly and is half transformed in 3 minutes, emitting α rays.

(2) The matter derived from radium A, called radium B, is half transformed in 21 minutes, but gives out no ionizing (α) rays during the process.

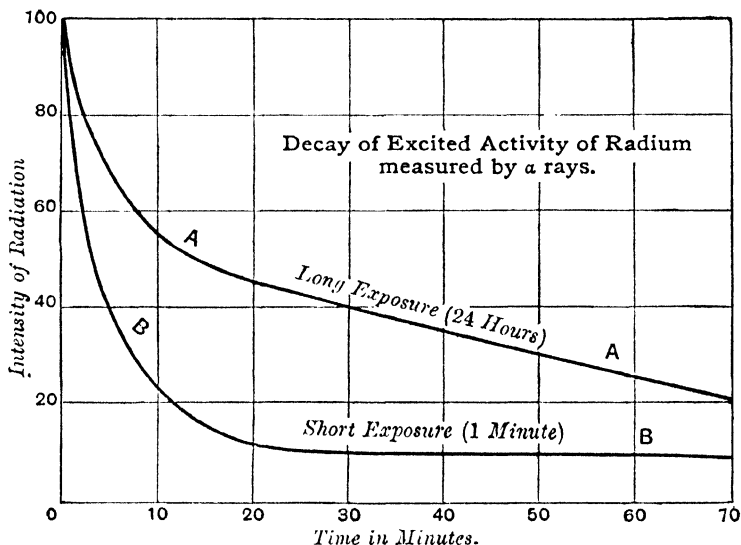


Fig. 8.

(3) The matter derived from radium B, called radium C, is half transformed in 28 minutes, and gives out α rays.

The sudden drop at the beginning is thus due to

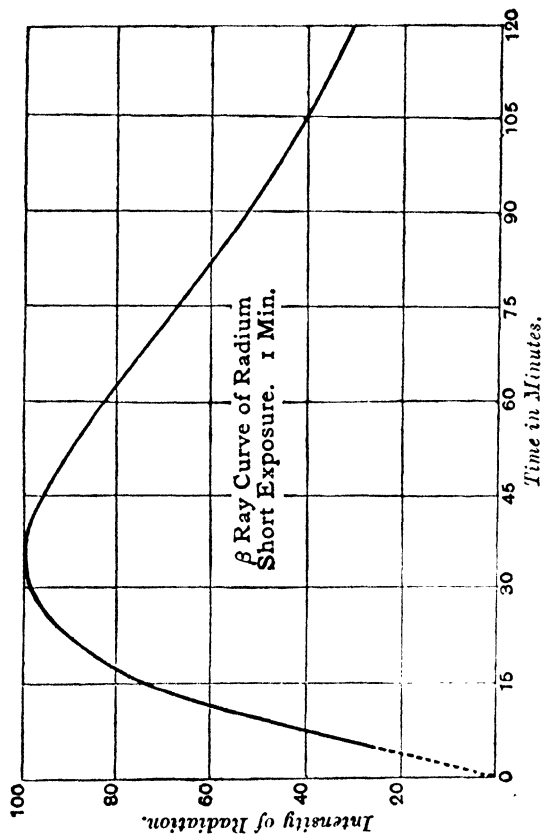


Fig. 9.

the rapid decay of radium *A*. In the middle stage the decay of radium *C* already produced is masked for a time by fresh production of radium *C*. When this has practically ceased, the third stage shows the decay of the remaining radium *C*.

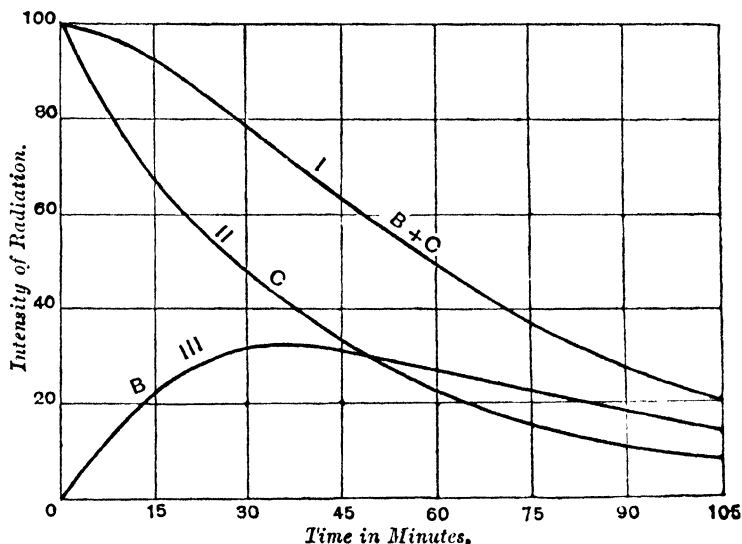


Fig. 10.

The curves for the same changes examined by penetrating β rays are given in figures 9 and 10 curve I.

The curve for a short exposure begins near zero. This shows that *radium A emits no β rays*. It then

risers to a maximum in 36 minutes and afterwards decays by an exponential law falling to half-value in 28 minutes.

With a long exposure not only will radium *A* have been formed on the wire, but radium *B* and radium *C* will have been produced from it.

Since (curve I, fig. 10) there is no sudden initial drop, as in the α curves, we see again that the radium *A* gives no β rays. Curve II shows how the radium *C* already existing when the wire is removed from the emanation would decay, by a 28 minute law. Curve III is the difference between curves I and II. It is *identical with the curve of fig. 9 for a short exposure*, rising to a maximum in 36 minutes and then decaying by a 28 minute law. But this represents the activity due to the fresh radium *C* produced from the radium *B*. It follows that the change from *B* to *C* does not *itself* emit any β rays, but only gives rise to them indirectly through the radium *C* which it produces. We have already seen that the transformation of radium *B* to radium *C* is not accompanied by α rays. This change is therefore a 'rayless' one. It shows that even a change which gives rise to no radiations may be traced, if it is followed by active changes, by the irregularities it introduces into their curves.

The results up to this point are summarized in the curves of fig. 11.

AA represents the α ray activity of the rapidly

decaying radium A . When this is subtracted from the curve $A + B + C$, there results the curve LL , which is analysed into CC and BB as before.

The conviction of the truth of this analysis would

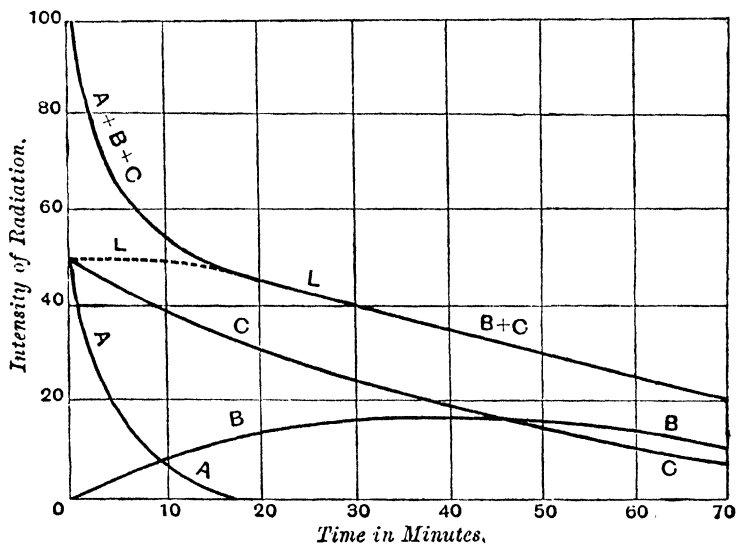


Fig. 11.

be immensely strengthened, could we lay before the reader the close agreement between the results calculated from the mathematical equations representing the curves and the values experimentally observed.

Activity of Slow Change.

A similar patient investigation has been applied to the minute activity that remains when the activity of rapid change has passed away. This residual activity has also been resolved into three stages:

(1) Radium *D*, derived from radium *C*, is transformed to half value, by another rayless change, in about 40 years. It produces radium *E*.

(2) Radium *E* is transformed to half value in about 5 days. It emits β and γ rays, and produces radium *F*.

(3) Radium *F* is transformed to half-value in 143 days. It emits α rays.

For historical interest the original analysis as given by Rutherford has been followed and the curves are those published in his Bakerian lecture. Since these initial experiments a large amount of work has been carried out to examine in the greatest detail this important series of changes. This has resulted in some modifications, which do not however affect the general theory.

For example, it has been found that radium *B* gives out *soft* β rays. These were not observed at first because they were absorbed by the screens used to absorb the α rays. Recently (Jan. 1912) it has been

found that radium *B* also emits some weak γ rays. The general analysis is not affected, but the periods ascribed to *B* and *C* are interchanged, the α ray product radium *C* having a period of 19.5 minutes while radium *B* has the longer period of 26.8 minutes.

Those who have not had an opportunity of following the theoretical analysis in detail, to whom therefore it may seem a slender basis for accepting the separate existence and properties of such substances as radium *B* and radium *C*, admittedly present only in infinitesimal quantity and in some cases not even indicating their presence by radiations, may perhaps be reassured to learn that it is now possible to isolate radium *B* and *C* by heating a platinum wire covered with the active deposit, and also by direct chemical methods. Thus, if the active deposit on a wire is dissolved in hydrochloric acid and a nickel plate is dipped in the solution, radium *C* is deposited on the plate and, when tested, proves to have a period of 19.5 minutes.

Radium *C* emits the swiftest α rays of the series and also very penetrating β and γ rays, the β rays attaining the extraordinary speed of .998, all but two-thousandths of the velocity of light. The explosion of the radium *C* atom is unusually violent, and recent results by Hahn and Fajans have shown that it appears to break up in two distinct ways ; for another

substance, existing in very small amount, has been discovered, which is half-transformed in 1.4 minutes and emits β and γ rays. Other instances are now known where one product can break up in two ways. Thus uranium breaks up into uranium X and uranium Y, and thorium *B* into thorium C_1 and thorium C_2 .

With radium *F* the series of the descendants of radium ends, for here the activity disappears. What may happen next is matter for surmise. Meanwhile its ancestors have been sought for with some success.

Radium itself falls to half-value in about 2000 years. This is a long life indeed, but a mere drop in the bucket compared with geological time. Had the whole earth been pure radium originally, the amount left now would have been utterly insignificant. Radium must therefore have a parent, and it must be one of the elements which have a heavier atom than radium itself. Uranium seemed the most likely. Its atomic weight is 238. It has now been proved that uranium gives out two α particles in changing to uranium X. That of uranium X is therefore 234. Radium is 226. But Ur X only gives out β rays. There is thus room for intermediate changes, in two of which an α particle counting 4 must be given out, between Ur X and radium. A search in this direction was suggested by many indications.

Uranium was always found in minerals containing radium. Again, it was remarkable that the greatest α ray activity in pitchblendes was between four and five times that of uranium. Now radium, in the course of the changes we have just traced, goes through at least four transformations in which an α particle is expelled. In an old mineral a state of equilibrium must have been reached and all these changes must be going on together. We should therefore expect about five times the activity of uranium. Acting on these hints, several investigators made a thorough search of all the known radiferous minerals. Strutt and Boltwood examined a large number taken from all parts of the world, and found that the ratio of the radium emanation they contained to the uranium present was almost exactly constant in spite of great differences in composition and locality of origin. This was a strong indication that uranium and radium were causally connected. Accordingly attempts were made to *grow* radium from uranium. Soddy examined the emanation produced from one kilogram of uranium nitrate which had been carefully freed from all trace of radium. Now calculation from their rates of decay shows that the amount of radium produced from one kilogram in a single day should be easily detected. But Soddy's experiment showed no result for two years, and then only a minute trace, 5.2×10^{-11} gm. per kgm. of uranium.

This disappointing result shows that radium is not directly produced from Ur X. But it is what would be expected if there were an *intermediate* product of very slow transformation, and therefore long life.

To understand this it must be remembered that in a state of equilibrium the amount of each product in the series transformed per second is the same. Hence for a product of slow transformation, since only an infinitesimal fraction of the amount existing is transformed per second, that amount must be correspondingly large. If, therefore, the uranium is cleared of Ur X and all its products, before any radium can again be detected, the uranium, itself transformed very slowly—it has a period of 6,000,000,000 years—must first accumulate the equilibrium amount of Ur X, while this in turn has to accumulate the very large equilibrium amount of the slow-transformation parent of radium.

As a matter of fact Boltwood has recently separated the long sought substance from uranium minerals, and named it Ionium. It is a close neighbour of thorium and has an atomic weight of 230. It emits an α particle and falls to half-value in about 200,000 years. Ionium can be initially freed from radium, and then in the course of a month a considerable amount of fresh radium, as tested by the emanation, is found to have been produced in it; moreover the growth is proportional to the time.

The Radio-active Families.

I.

Substance and atomic weight	Period of fall to half-value	Radiations emitted	Range of α particles in air at 15° C. centimetres v. p. 138
Uranium, 238.5	6×10^8 years	α	2.50
Uranium ₂	2×10^6 years	α	2.90
Uranium X 230.5	24.6 days	$\beta\gamma$	
Ionium 230.5?	200,000 years	α	3.0
Radium 226.5	2000 years	$\alpha\beta$	3.30
Emanation	3.85 days	α	4.16
Radium A	3 mins.	α	4.75
Radium B	26.8 mins.	β	
Radium C	19.5 mins.	$\alpha\beta\gamma$	6.94
Radium D ₁	1.4 min.	$\beta\gamma$	
Radium D ₂	15 years		
Radium E ₁			
Radium E ₂	4.8 days	β	
Radium F (Polonium)	140 days	α	3.77

The break-up of radium C is abnormal. Geiger and Marsden find that in this case, as also for thorium C and the emanations of thorium and actinium, the scintillations from the α particles occur in *pairs*. Either, then, the atoms break up in two different ways, or there are two successive products, one of them very short-lived.

II.

Substance	Period of fall to half-value	Radiations emitted	Range of α particles in air. Centimetres v. p. 138
Thorium 232·5	3·10 ¹⁰ years	α	2·72
Mesothorium ₁	5·5 years	rayless	
Mesothorium ₂	6·2 hours	$\beta\gamma$	
Radio-thorium	2 years	α	3·87
Thorium X	3·70 days	$\alpha\beta$	4·30
Emanation	54 secs.	α	5·00
Thorium A	·14 sec.	α	5·70
Thorium B	10·6 hours	β	
Thorium $\left[\begin{smallmatrix} C_1 \\ C_2 \end{smallmatrix} \right]$	60 mins. ?	α α	4·80 8·60
Thorium D	3 mins.	$\beta\gamma$	
Actinium			
Radio-actinium	19·5 days	$\alpha\beta$	4·60
Actinium X	10·5 days	α	4·40
Emanation	3·9 seconds	α	5·70
Actinium A	36·1 mins.	β	
Actinium B	2·15 mins.	α	6·50
Actinium C	5·1 mins.	$\beta\gamma$	5·40

For the two emanations the latter view is confirmed by a study of

The complete family tree of the uranium-radium family as far as it is known at present is given in tabular form, and similar tables are added for thorium and actinium.

The second column gives for each product the time it takes to fall to half-value. This is a constant by which *the product can be identified*.

By means of these constants it has been shown

the ranges of the α particles emitted. From Rutherford's law connecting the life of a product with the range of its α particle, it appears that one of the products of the thorium emanation has a period 0.14 sec., and the corresponding product of the actinium emanation has the minute period, .002 sec.! A new α ray product with this period must therefore be inserted in the table ahead of actinium *A*.

The existence of these short-lived products may be shown by a pretty experiment. An endless charged wire is run on insulating pulleys at high speed. In passing through a box it is exposed to actinium or thorium emanation, and immediately outside it runs along a zinc-sulphide screen, which is seen to be lighted up for some distance from the box. From the speed of the wire the life of the α ray product deposited on it by the emanation may be determined.

For radium *C* and thorium *C* (or, rather, thorium *B*) it would seem that there is really a double break-up, a branch being thrown off from the main line of descent. Some recent work by Marsden and Darwin tends to show that one-third of the atoms of Th *B* break up into Th *C*₁, which emits α rays of range 4.8 and produces the $\beta\gamma$ ray product Th *D*; while two-thirds break up into Th *C*₂, a β ray product whose subsequent history is not yet known. Perhaps this is because the product it ends in emits the fastest α particles known, with a range 8.6, so that by Rutherford's law its period should have the incredibly minute value 10^{-12} sec.

that the active principle in polonium is really the seventh disintegration product of radium, radium *F'*; and the radio-lead owes its activity to radium *D* and its products. These discoveries are indicated in the table.

The atomic weight falls by 4 every time an α particle is ejected; but is not diminished appreciably by the expulsion of an electron, or a γ ray. The series starts with uranium 238; this is now known to give out two α particles, with the formation of a second substance, uranium 2, before uranium X 230 is reached. Ur X only gives out β and γ rays, producing ionium, still 230, and then by the expulsion of another α particle radium is reached with atomic weight 226.

What becomes of radium *F'*? Since it gives out an α particle, the next product should have an atomic weight 206, which is near that of lead. Accordingly Boltwood early suggested that the final result, when the series of active changes is accomplished, should be lead, an idea supported by much evidence as to the proportion of lead found in the radiferous minerals, similar to that which suggested the descent of radium from uranium.

The final product of the thorium series is not so certain. Six α particles are given out, so that its atomic weight should be $232\cdot5 - 24 = 208\cdot5$, which suggests bismuth, but the evidence from the minerals

does not in this case fall into line. This may be due to the double break-up at thorium *C*, leading perhaps to two end-products.

Nothing is known of the atomic weights of the actinium series. There are indications that this series is a branch from the uranium-radium family, possibly taking its rise at the abnormal break-up of radium *C*.

The Disintegration Theory has received (*Proc. Roy. Soc.* Jan. 12, 1911) a beautiful confirmation. Dr Gray and Sir William Ramsay have succeeded in directly determining the molecular weight of the radium emanation, by weighing it, and measuring its volume, temperature and pressure. The total volume of emanation available was less than one-tenth of a cubic millimetre. Yet not only was this mere pin's point of gas weighed, but elaborate corrections were made for its decay during the experiment, for the amount of helium occluded in the tube, and other minute sources of error. The results of five experiments range between 227 and 218 with a mean of 223. Since the equivalent of radium is now established at 226·4, that of the emanation, resulting from the loss of one α particle, should theoretically be $226\cdot4 - 4 = 222\cdot4$, an extraordinarily close agreement.

The work of Gray and Ramsay was only rendered possible by an achievement in the southern

hemisphere, which well illustrates the gain of power to science through the world-wide co-operation of disinterested investigators. Dr Steele and Mr Grant of the University of Melbourne have recently constructed a balance with a girder beam made of fine silica rods, and devised a method of weighing by displacement with it which allows the estimation of *one quarter of a millionth of a milligram*. The limit of sensibility of the finest assay balance has hitherto been one two-hundredth of a milligram. This marvellous increase in delicacy is no more than was required for Gray and Ramsay's experiment, for the total quantity of emanation dealt with weighed only about 700 millionths of a milligram. The credit of a wonderful feat of manipulation is thus shared between two hemispheres.

CHAPTER VII

VERIFICATIONS AND RESULTS

THERE are four stages in the establishment of any natural law. First, *observation*, the recognition of some new fact or relation. This is usually the work of genius. It requires insight to descry amidst the familiar what has always been there but hitherto has escaped notice. Some discoveries appear accidental, but these accidents only happen to those with seeing

eyes and imagination to grasp the significance of what the dull and incurious would pass as unimportant. Then comes *experiment*, by which the new facts are made sure and disentangled from what is irrelevant. Next, the consequences of the new view are traced by *deduction* in detail. Lastly comes *verification*, when those consequences are compared with further experimental results.

The Disintegration Theory described in the last two chapters effects so profound a revolution in accepted ideas that it will be well to collect a few leading verifications. But it must be borne in mind that these are only samples of a vast mass of results which, as experimental methods improve, are found in increasing agreement with calculation.

1. *Volume of the Emanation.*

Quite early, in the course of an investigation of the charge carried by the α particles, Rutherford calculated the amount of emanation that should be obtained from one gram of radium in radio-active equilibrium. Apart from the very slow residual changes, which for this purpose may be neglected, there are then four sets of α particles being emitted, from the radium, the emanation, radium A, and radium C. When the radium is freed from the emanation and subsequent products, it still retains

its own α activity which is one quarter of the total. This is called its minimum activity. The minute current carried by the α particles from a known weight of radium bromide at this minimum activity was measured on a Dolezalek electrometer. If each α particle carries the ionic charge, then by division into the total charge carried it appears that the number of α particles emitted per second is 3.6×10^{10} *, *i.e.* thirty-six thousand million. For each α particle emitted there is a corresponding atom of emanation produced. Now the rate of decay of the emanation is known from its curve. In fact 1 particle in every 463,000 breaks up per second. But in *equilibrium* the number of particles breaking up must be equal to the number of new particles produced. Thus 3.6×10^{10} must be one 463,000th part of those existing at any moment. The number of molecules of emanation to be expected from one gram of radium bromide, when the whole amount stored in it is disengaged by solution, should thus be

$$463,000 \times 3.6 \times 10^{10},$$

i.e. 1.7×10^{16} . The fraction of a cubic centimetre that these would occupy at ordinary temperature and pressure is obtained by dividing by Avogadro's constant, the number of molecules of any gas in a cubic centimetre. This is 3.6×10^{19} . The volume of the

* But see p. 102.

emanation from one gram of radium bromide is thus $\cdot 46 \times 10^{-3}$ c.c., *i.e.* $\cdot 46$ cubic millimetres. Allowing for the chemical composition of the bromide (RaBr_2) this shows that for *pure* radium the amount of emanation would be $\cdot 82$ cubic millimetre per gram.

When Ramsay and Soddy at last succeeded in isolating and measuring the minute bubble of emanation from 60 milligrams of radium bromide, they concluded that a gram of pure radium should produce about one cubic millimetre of emanation, a result sufficiently concordant with calculation when the extreme difficulty of the experiment is remembered. Recent investigations (1908) have, as we shall see, brought about a much closer agreement.

2. *Counting the Atoms.*

Since on the assumption that an *a* particle carries the ionic charge, a gram of radium bromide emits at *minimum* activity thirty-six thousand million *a* particles per second, each representing the break up of an atom, it would seem a most hopeless quest to detect the effect of a single *a* particle and so count the atoms destroyed. Yet this is what has been accomplished.

The action of individual *a* particles was first made visible in the little instrument invented by Sir William Crookes, the spinthariscopes. A needle dipped for a

moment in a weak radium solution is placed close in front of a small zinc sulphide screen, and examined by a lens. When the eye has been made sensitive by remaining for some minutes in the dark, the surface of the screen is seen to be twinkling incessantly with thousands of points of greenish light. These are due to the impact of α particles discharged by the radium, but the exact nature of the process, and whether each sparkle indicated a single α particle, were questions it was not easy to determine.

In 1908 Rutherford and Geiger devised an electrical method of counting the particles. An α particle expelled from radium produces more than 100,000 ions in air before it is stopped. Calculation from this datum shows that while the detection of a single α particle by its ionizing effect should be just within the range of the most refined experiment, it would be beset with grave difficulties. Now Townsend had shown that when ions are produced in an electric field their speed may be increased till, first, the negative ions and, later, when the potential gradient approaches the sparking limit, the positive ions produce many more ions by collision with the neutral atoms of the gas. It occurred to Rutherford to employ this method of magnifying the ionizing effect of a single α particle.

The source of α particles was a small disc exposed for some hours to radium emanation. This was carried on the end of a small iron cylinder which

could slide along a long glass tube and be moved to any position by means of a magnet without opening the tube. Fifteen minutes after removal from the emanation the radiation from the disc was practically reduced to that from radium *C*. At the other end of the tube, some four metres distant, was a small opening, covered with a thin mica plate, into the exhausted testing chamber, which consisted of a cylinder with a central insulated wire. The voltage applied between the wire and the cylinder was adjusted so that the ionizing effect of a constant source of γ rays was multiplied several thousand times.

The α particles are shot out in all directions, so that a few of them enter the chamber through the distant narrow aperture. It was found possible to arrange that from two to five per minute entered the vessel, each one signalling its arrival by an unmistakable throw of the needle of an electrometer connected in the usual way with the testing vessel. The results were admirably consistent, and it was then easy to calculate from the known size of aperture and distance from the source what must be the total number of particles emitted in all directions. In three experiments when the source was distant three metres and a half from the aperture, only one particle out of 125,000,000 emitted would get into the vessel.

Making all corrections, Rutherford and Geiger concluded that the number of α particles emitted

from one gram of radium itself per second is 3.4×10^{10} , instead of 3.6×10^{10} as assumed above. If the radium is in equilibrium with its products, since the emanation, radium *A*, and radium *C* each give out an α particle for every one given out by the radium, the number will be four times as great.

Experiments were then carried out in which the number of scintillations were counted under a microscope. The close concordance of the results proves that in the spinthariscopes each scintillation corresponds to the impact of one α particle.

The visible detection, by two methods, of the effect of a single particle of atomic size is certainly one of the most remarkable and least expected triumphs of experimental skill.

3. *Proof that α particles are Helium atoms.*

The determination of the number of α particles emitted, by two methods of directly counting them, enabled Rutherford and Geiger to settle the vexed question whether these particles are really helium atoms, as had early been suggested by Rutherford. In 1908 they repeated the experiments for measuring the total charge carried by the α particles from a definite amount of radium, and showed from a series of very consistent results that the charge of an α particle is 9.3×10^{-10} electrostatic units.

The ionic charge, as we have seen, had been found by J. J. Thomson to be 3.4×10^{-10} . Other determinations by different methods were, by Townsend 3×10^{-10} ; H. A. Wilson 3.1×10^{-10} ; Millikan 4.06×10^{-10} and more lately 4.9×10^{-10} . Rutherford and Geiger calculated the value 4.1×10^{-10} by an ingenious application of the new method of counting the α particles to Boltwood's value of the life of radium, which however was too low. Knowing the number of atoms of radium which break up per second and from its decay curve the fraction which this is of the whole, we obtain the number of atoms in a gram of radium; thence, from the atomic weight of radium, the number in a gram of hydrogen; and finally from the hydrogen liberated by a definite amount of electricity in electrolysis, the charge carried by each atom.

But then, what meaning is to be attached to the value 9.3×10^{-10} for the charge of an α particle? It must be some multiple of the unitary charge carried by an ion. Is it twice, or three times as great? Rutherford has given very strong reasons for believing that the early determinations of the ionic charge were all too low, one source of error being that no allowance was made for evaporation from the drops during the settlement of the clouds used for counting the molecules (v. Chapter II). In that case the α particle must carry *double* the ionic charge, and the latter must be taken to be not 3.4×10^{-10} but

4.65×10^{-10} . This would agree with recent values obtained by Planck from the theory of radiation and by Regener, who introduced a beautiful modification of Crookes' spinthariscopes method by counting the scintillations produced by the α particles from polonium upon a small diamond plate.

Now the ratio e/m for an α particle is about half that for the hydrogen atom in electrolysis. If its charge is double, then the mass must be four times that of a hydrogen atom. To be precise, it comes out 3.84, while the atomic weight of helium is 3.96. Allowing for experimental errors, it seems reasonable to conclude that an α particle is an atom of helium carrying a double ionic charge.

The first attempts to show experimentally that helium is produced from the radium emanation were made by Ramsay and Soddy in 1903, following on Rutherford's suggestion in 1902. Dewar and Curie made similar experiments afterwards. In each case a quantity of emanation was enclosed in a small spectrum tube and the spectrum examined day by day. The helium lines gradually appeared.

These experiments were of extreme difficulty and it might, as indeed it was, still be argued that the helium had nothing to do with the α particles but was a by-product of the explosion of the radium atom like the emanation itself, one atom of helium being produced and one of emanation for every α

particle expelled. But in 1909 Rutherford and Royds devised a more direct demonstration. They succeeded in blowing very thin glass bulbs, less than one hundredth of a millimetre ($\frac{1}{2500}$ th of an inch) in thickness, which would allow the α particles to pass through the glass and yet stand atmospheric pressure. One of these bulbs filled with radium emanation was enclosed in an outer glass tube which was exhausted, and the spectrum obtained when a current was passed through the outer tube was examined. For twenty-four hours no sign of helium appeared. After four days the helium lines in the yellow and green were seen. In six days the complete spectrum of helium was obtained. Since nothing could gain access to the outer tube except the α particles fired through the walls of the thin glass bulb, it was impossible to avoid the conclusion that the α particles are themselves atoms of helium. As a check experiment, the inner bulb was then filled with helium under pressure, but no sign of helium appeared in the outer tube.

4. *Rate of Production of Helium.*

When radium has stood long enough to be in equilibrium with its products there are four products giving out α particles :—radium, the emanation, and radium A and C. Each of these gives out, by the

counting experiments, 3.4×10^{10} particles per second. All four together give out in one year

$4 \times 3.4 \times 10^{10} \times 365 \times 24 \times 60 \times 60$ particles per gram.

Dividing by 2.72×10^{19} , the revised value of the number of molecules in a cubic centimetre of any gas, we find the yearly product of helium from a gram of radium to be .158 c.c., or 158 cubic millimetres. Recent experiments, by Dewar in 1910, gave a yield of 170 cub. mm.; and still more recently Boltwood and Rutherford have obtained the value 156 c.c. This, as the authors say, is 'disagreeably' close to the theoretical number, but experiments by two different methods gave the same result.

Similarly, if the latest values are employed, the volume of emanation from a gram of radium is found to be .585 cubic mm. instead of .82; and this is in agreement with the best experimental measures, viz. .61 cub. mm. (Rutherford, 1908), .58 mm. (Debiere, 1909), .601 mm. (Ramsay and Gray).

For comparison with the atomic constants given in Chapters I and II we may here collect the results based on Rutherford's direct counting experiments.

Number of α particles per second

from 1 gram of radium at mini-

mum activity 3.4×10^{10}

Charge of an α particle 9.3×10^{-10} E.S.

Ionic charge (half above), *i.e.* charge

on hydrogen atom 4.65×10^{10}

Consequent number of hydrogen

atoms in cubic centimetre 2.72×10^{19}

Mass of hydrogen atom 1.61×10^{-24} gm.

Volume of emanation per gram of

radium 585 cub. mm.

Volume of helium per gram per

year 158 cub. mms.

5. *Recoil of the Atoms*¹.

If it is true that the atoms of any product, in the act of transformation to the succeeding product, fire out an α particle with high speed, then the atoms of the new product so formed should *recoil* with the same momentum as that communicated to the α particle, exactly as a gun recoils on discharging its projectile. This is actually found to be the case. A metal plate set near a radio-active substance is bombarded by these recoil-atoms, and collects the succeeding product in a pure state. This method is now freely employed to separate out some products, such as radium *B*, whose existence could only be inferred from the curves, and by means of it some new products have been detected. Moreover, the recoil-atoms can be deflected in a magnetic field. Their deflection is half that of the α particle, and

¹ Russ and Makower, *Proc. Roy. Soc.* 1909.

therefore they carry half the charge of an α particle, *i.e.* the ionic charge. This method also affords the only means of determining the atomic weights of many products which exist in very minute quantity.

6. *Emission of Energy by Radium.*

Although it was certain that energy was being constantly emitted by the radio-active substances, it came as a startling surprise when P. Curie and Laborde in 1903 announced that radium compounds maintained themselves permanently at a temperature two or three degrees higher than their surroundings. Measurements by the Curies, by Rutherford and Barnes, and later by Callendar, Ångström, Schweidler and Hess, the latter using the large quantity of radium separated by the Austrian Government, show that 1 gm. of radium emits heat at the rate of 132 gram-calories per hour, enough to melt 1.6 times its own weight of ice per hour, and that three quarters of the heat emission is due to the emanation and its products. This is what should be expected. From their masses and velocities it is easy to show that the energy of an α particle is about one hundred times that of the average β particle. The heating effect is thus due chiefly to the α particles, and the emanation, with its products radium A and C, emits three α particles to each one emitted by radium

itself. As a further verification, the heat calculated from the number of α particles emitted and their known energy is in fair agreement with the value found experimentally. This gives a total disengagement of heat from one gram of radium, before it disappears, about one million times as great as is evolved in the formation of one gram of water. One pound of the emanation would at its maximum intensity radiate energy at the rate of about 10,000 horse power.

This large emission of energy from the radio-active bodies throws an interesting light on two questions which have long been the subject of controversy, the age of the earth and the source of the heat of the sun.

7. *The Age of the Earth.*

In descending a mine it is found that the temperature rises about one degree Fahrenheit for every 50 or 60 feet of descent. Lord Kelvin showed long ago that if the earth be regarded as a body cooling freely in space without internal supply of heat, this temperature gradient indicates that about 100,000,000 years ago the earth must have been a molten mass. This period, long as it seems, is quite insufficient for geologists to account for the deposition of the observed strata, and for biologists, to allow for the development of known types from primordial life. Hence a somewhat embittered controversy.

The discovery that radium and its emanation, not to speak of the other radio-active elements, are widely distributed, though in minute proportion, throughout the atmosphere, the springs, the rocks and soils of the earth's crust removes the difficulty. Henceforth the physicists can make the geologists and biologists happy with a blank cheque on eternity, so far as this argument is concerned. The present loss of heat from the earth is about 2.2×10^{-7} calories per c.c. per year which could be supplied indefinitely by the presence of 2×10^{-13} gram of radium per c.c. Now Strutt finds there is on the average 4×10^{-12} gram of radium per c.c., *i.e.* about twenty times more than is required. There is thus no reason why the present state of things should not have been maintained for far longer periods than 100,000,000 years. On the contrary, it is necessary to suppose that the percentage of radium found at the surface is confined to a crust about forty miles thick, and that the interior is free from radium. This would indicate a temperature of about 1500° C. for the core, a value not inconsistent with the temperature of the lava from Mount Etna, 1060° C. The great heat met with occasionally, as in the boring of the Simplon tunnel, is also accounted for, since in regions rich in activity the temperature gradient is abnormally high.

8. *The Age of Rocks.*

But the discoveries of the last ten years have done more than remove a difficulty for the geologists. They supply a means of directly estimating the age of radiferous rocks and, by implication, of the strata in which they are found, through the estimation of their content of helium. This element has a strange story. Its existence was first inferred from certain spectral lines only seen in a total eclipse of the sun. Hence the name. Then it was most unexpectedly disengaged from cleveite, a heavy mineral. It is only found in radio-active rocks and is occluded in them where it is produced, as uranium degrades into radium and its successive products. If therefore the annual production of helium due to the uranium present be divided into the total amount of helium found, some hint should be obtained of the number of years during which it has been storing up.

Thus Fergusonite contains 7 per cent. of uranium and 1·8 cubic c.c. of helium per gram. Now one gram of uranium, with its products, gives out a particles to the extent of $1\cdot08 \times 10^{-7}$ c.c. of helium per year. Thus the age of Fergusonite should be

$$\frac{1\cdot8}{\frac{7}{100} \times 1\cdot08 \times 10^{-7}} = 2\cdot4 \times 10^8,$$

i.e. about 240 million years.

Thorianite contains the unusual amount of 9·5 c.c.

of helium per gram. In this case Strutt has estimated the age by directly measuring the annual production and dividing into the total found¹.

Another point which may interest biologists as well as geologists arises from the discovery of radium emanation in mineral springs. It may possibly be the secret of their medicinal effects, which in many cases cannot be traced to any special chemical composition, and disappear when the waters are bottled and sent to a distance. Now the emanation certainly has a physiological effect, and would have passed away in less than a month.

9. *Age of the Sun.*

The discovery of radium has not brought quite the same relief to astronomers with regard to the question of the source of the sun's heat. Lord Kelvin in a famous passage discussing the theory of gravitational contraction from a nebula, the only one which can at all account for the sun's enormous output, concludes that it is 'on the whole probable that the sun has not illuminated the earth for 100,000,000

¹ The age may also be estimated by the content of lead. Helium, since part of it may escape, gives a minimum value; lead, which does not escape and may not all have been formed *in situ*, gives a maximum, from two to four times the value from helium. Thus for the Carboniferous Limestones (Haematite, Forest of Dean) Strutt assigns an age of 150 million years from helium, and 340 million from the lead-content.

years and almost certain that he has not done so for 500,000,000 years. As for the future we may say, with equal certainty, that inhabitants of the earth cannot continue to enjoy the light and heat essential to their life for many million years longer, *unless sources now unknown to us are prepared in the great storehouses of creation.*

Had Kelvin had at his disposal Langley's instead of Pouillet's measurement of the solar constant of radiation, his hundred million would have been reduced to sixty; and Sir George Darwin has given reasons why this again should be brought down to twelve.

On the discovery of radium the cautious passage we have italicised seemed almost prophetic. It is true that no γ rays from radium have been detected in sunlight; but this is not surprising since the atmosphere which shields the earth is equivalent to a thickness of thirty inches of mercury. Nor have the radium lines yet been observed in the solar spectrum. But this is not the difficulty. To account for the sun's output of 430 calories per hour per cubic metre, would require 3.2 gms. of radium per cubic metre, since each gram gives 132 calories. Now the sun's density is 1.44, so that he should contain 1.8×10^{-6} parts by weight of radium. This is five or six times too great for radium in equilibrium with uranium.

Radium cannot, as was at first supposed, supply the whole solar output. But it may very well be a large contributor; and it is possible that at the high temperatures existing in the sun radio-active processes may go forward at a greater rate than at the temperatures available on earth, while other instances of transformations in which atomic energy is unlocked, perhaps without the accompaniment of radio-active phenomena, may be taking place.

10. *Cosmical Effects.*

The aptness of electrons and positive ions to form nuclei for the condensation of vapours has been applied by Arrhenius to explain a number of phenomena which have long puzzled astronomers.

1. Comets' Tails. These are produced as the comet approaches the sun: shoot out to enormous distances, always pointing away from the sun whatever the direction of the comet's motion, so that in departing the tail precedes the head; and, as the comet sweeps round the sun at perihelion, are 'brandished,' as Herschel says, through half a circle without injury,—inconceivable behaviour for such an enormously extended appendage of matter which, from its transparency to the stars and lack of attraction on the planets, must be far more rarefied than our best earthly vacuums.

Arrhenius suggests that the hydro-carbon vapours roasted out of the comets' materials by the tremendous heat of the sun condense into droplets on the electrons which the sun, as a very hot body, must discharge into space, and are then driven backwards by the pressure of the sun's light. This pressure, predicted and calculated by Maxwell in 1867, is so minute on surfaces of ordinary size, that it was only discovered experimentally in 1904. But since the surface exposed to pressure falls off as the square of a particle's diameter, while the solid contents subject to gravitation fall off as the cube, as we proceed to smaller and smaller particles there must come a time when the light-pressure will balance the weight. For liquid droplets this 'critical' value is about one micron. For still smaller diameters the light-pressure will exceed the solar gravitation, and may be as much as eighteen times as great. Here at last is the 'violent repulsive force from the sun,' the 'negative gravity' so long sought in vain. Such a force would make light of projecting a tail 20,000,000 leagues in two days, as Newton observed in the case of the great comet of 1680. It is not, then, the *same* tail which is brandished, but the tail is constantly being re-formed, and always in the direction away from the sun.

2. The Aurora. The vapours ejected from the sun must condense and be driven off in the same

way, with speeds which would carry them beyond the earth's orbit in a few hours. On this Arrhenius founds plausible explanations of the Corona and Prominences observed during eclipses, but especially of the Aurora. The flights of droplets, each carrying a negatively charged ion, arriving over the equator are caught by the lines of force of the earth's magnetic field, which arch from pole to pole, and, by well-known electrical laws, are obliged to follow them in spirals towards the poles. In their passage through the rarefied upper air they give rise to the shifting lights which may be mimicked on a small scale by the discharge of similar particles from the kathode of a vacuum tube. The writer has suggested that the strange and beautiful 'curtain' auroras, taking the form of long fringes of coloured light, hanging in vertical lines and sharply terminated at the lower edge, may be due to similar discharges of α particles, which would have a long range in the rare atmosphere at the upper levels, but be suddenly extinguished in the end.

The theory solves another difficulty. It had never been understood how disturbances on the sun, whatever their violence, could *directly* affect the magnetic state of the earth. Yet when records of the number of Sun-spots, Magnetic Storms and Aurorae are plotted over a long interval of years, the three curves follow each other closely, showing the

same slow secular changes, the well-known 'eleven year' period, the annual variation, and even two smaller monthly variations; so that there is an undoubted connection between them. It is obvious on Arrhenius' view that the flights of electrons are the equivalent of negative currents and must produce magnetic disturbances on earth; and he is able to account in detail for the variations on the very reasonable hypothesis that the sun-spots, as the seat of violent eruptive storms, are the most prolific source of electrons.

CHAPTER VIII

THE OBJECTIVE REALITY OF MOLECULES

A STUDENT of the tables on pp. 10, 106 may well be staggered by the inconceivable minuteness of some of the quantities in which he is called upon to believe, and perhaps ask himself whether in the kinetic theory of matter which leads to such results we are proceeding upon any basis of reality, or whether it be not after all merely an ingenious hypothesis. It is true that by means of it we can co-ordinate the experimental laws discovered in many branches of physics; and the conclusions drawn from widely different physical phenomena as to the size, mass and number

of the atoms, and the charge of an electron, show a remarkable concordance, at least as to the order of magnitude. But the largest molecule is far beyond direct sense perception; the atom is a long stage beyond the molecule; and the electron is another thousandfold stage beyond the atom. Moreover the violent agitation in which these supposed entities must be conceived to exist, not only in gases but even in liquids and solids, appears to contradict the first direct evidence of the senses. Newton's warning 'Hypotheses non fingo' seems in place at this point, and a verification which should give to the molecule and the atom the character of '*verae causae*' would be welcome indeed.

Most opportunely such a verification is to hand in Perrin's recent study (1908-10) of the so-called Brownian movement, which renders visible in the microscope not, indeed, the molecules themselves, but a direct effect of their perpetual movement in a liquid. The phenomenon was first noticed in 1827 by the English botanist Robert Brown, shortly after the discovery of the achromatic objective. Brown, while engaged in examining pollen grains, observed that very minute material particles suspended in a liquid were never at rest, however long the liquid had been standing, but subject to incessant, irregular movements, so that they described paths, not curvilinear, but made up of short disjointed straight-

line sections, neighbouring particles darting in quite different directions as though buffeted hither and thither by some hidden incalculable force.

No one at the time realised the true significance of Brown's observation. But in 1863, shortly after the development of the kinetic theory of heat, Wiener cited the Brownian movement as a proof of the molecular agitation in liquids, and in 1877 PP. Delsaulx and Carbonelle assigned it to the same cause. The latter ingeniously explained its mode of action. According to the kinetic theory the pressure of a gas or liquid upon any surface exposed to it is due to the averaged impacts of myriads of molecules striking it. A moderately small particle must be struck by such a vast number of molecules per second that the molecular pressure of the liquid averages out to be the same on all sides. It is thus free to settle under the steady pull of gravity, as it is observed to do. But for particles beneath a certain size the case is different. Their surface does not admit of enough impacts for the average to hold. At any instant they may be struck on one side by more molecules, or with momentarily greater velocities, than on the other, and thus they are driven hither and thither with the irregular motions observed. The smaller the particles, the more vivid and irregular will be their motions, and this, too, accords with observation.

In 1888 Gouy excluded by careful experiments

all other causes which had been suggested for the Brownian movement. It could not be due to vibrations transmitted from the ground, for it goes on at night in the deeps of the country with the same activity as amid the heavy traffic of a city. Nor to the convection currents which make the motes dance in a sunbeam, for these may be excluded without affecting the motions. Moreover, the motes move in streams showing the course of the currents, while the most striking characteristic of the Brownian movement is that two particles, however near, are subject to motions which have no apparent relation to each other. Lastly, although light is now known to exert a minute pressure which may become important in the case of very small particles, it cannot be concerned here, since the light used for illumination may be suddenly varied a thousandfold without effect.

The strong presumption afforded by these researches, that in the Brownian movement the molecules may be seen visibly at work, has been converted into a certainty by Perrin's quantitative study of the phenomenon since 1908. Conversely, he has been able to deduce verifications of some of the most abstruse mathematical results of the kinetic theory; and values for the number, size, and charge of the atoms which agree very closely with those obtained from the theory of radio-activity.

The labours of the founders of thermodynamics

(Clausius, Maxwell, Gibbs, Boltzmann) lead through some of the most difficult regions of modern mathematics to certain famous theorems—theorems which are necessarily statistical, since among the jostling crowd of molecules every variety of movement must occur many millions of times every second. One is, that the *mean* energy of the molecules of a gas or liquid in equilibrium is shared equally between all the different types of motion open to the molecules. For instance, the mean energy of translation in any direction is equal to the mean energy of rotation about any axis. Another gives the law of distribution of velocities among the individual molecules. It appears that the number of molecules which at any instant have a speed differing from the mean speed by a certain amount is fixed by Laplace's formula in the Theory of Errors, and corresponds to the number of bullets, fired at a target under similar circumstances, which will be found at a given distance from the bull's eye.

The equations and formulae which express these propositions accurately are too complicated to be understood, except by mathematicians, and a verification would seem at first sight out of the question. But Perrin betakes himself to a practical consequence of the theorems. Just as Laplace had deduced the law of distribution of molecules in the atmosphere under gravity, showing that for equal heights of ascent the

number of molecules (and therefore the density and barometric pressure) must fall off in geometrical progression, so Perrin, on the assumption that the Brownian particles behave among the molecules of the liquid exactly as molecules of a larger size, deduced a similar formula giving the same exponential law of distribution. But there was this difference, that, whereas Laplace's law of atmospheric pressure could be verified by easy observations taken over a vertical height of several miles, Perrin had to carry out the whole of his experiments upon a layer of liquid one-tenth of a millimetre deep !

The first experimental difficulty was to obtain an emulsion containing grains of the requisite fineness and of uniform size. Two substances were employed, gamboge and mastic. From these by an ingenious process of 'fractional centrifugation' emulsions were prepared of uniform fineness, with grains whose radius might at will be made anything from one-tenth of a micron—a micron is the thousandth of a millimetre—to 12 or 13 microns. A thin layer of emulsion, about 100 microns or one-tenth of a millimetre deep, was placed in a shallow glass cell under a high-power microscope. With the high power employed there is very little depth of focus, so that only one level of the liquid could be studied at a time. But this level could be varied by raising or lowering the microscope by the micrometer screw,

which allowed an adjustment to within a quarter of a micron. The counting presented difficulties, for not only are all the grains in rapid irregular motion horizontally while they remain in the plane of vision, but the slightest vertical movement upwards or downwards causes them to disappear instantly, while swarms of other grains, rising or falling into the plane of vision, flash into view in their turn. The field was therefore limited by a diaphragm pierced with a fine needle, so that not more than five or six grains were in view at any one instant. These the eye could take in at a glance when the field was instantaneously illuminated at intervals of 10 or 15 seconds, and observations were thus carried on at different levels, in some series as many as 13,000 grains being counted.

It was found that within these narrow limits of working the exponential law of distribution held good, as it does for the molecules of the atmosphere. How accurately, may be seen from the results of two sample experiments.

With grains of radius 0.14 micron in a layer of liquid 110 microns deep, the grains were counted at five levels taken every 25 microns, the highest level being five microns below the surface of the liquid. The numbers found, reckoning downwards, were proportional to

100, 116, 146, 170, 200,

whereas the strict law would require

100, 119, 142, 169, 201.

With larger grains (radius 0.212 micron) so as to give a more rapid diminution of density, reckoning upwards at successive vertical heights of 30 microns, the numbers were, as

100, 47, 22.6, 12,

while the law requires

100, 48, 23, 11.1.

The close agreement of these observed numbers with theory, showing that so far as the law of distribution is concerned the Brownian grains behave exactly like molecules of a larger size, is in itself remarkable. Still more striking are the results when, conversely, it is sought to determine the mean energy of the grains, which, if the Brownian movement is really the result of molecular bombardment, should come out identical with the mean molecular energy upon the kinetic theory, whatever the size of grain employed, and by implication yield another determination of a fundamental physical quantity known as Avogadro's constant, that is, the number of molecules contained in a cubic centimetre of any gas at standard temperature and pressure. This may be done. For the exact equation expressing the law of distribution of the grains involves the mean granular energy

together with the radius and density of the grains, so that if the radius and density can be *measured*, the equation will give the mean energy.

Perrin measured the density by two different methods with results which were concordant within 1 or 2 parts in a thousand. Thus, with mastic one method gave a density 1.063, the other 1.064. The radius was determined by two methods of direct counting and measurement, and also by applying Stokes' formula to the rate of fall of a cloud of grains through the emulsion, the method employed by J. J. Thomson and C. T. R. Wilson (Chap. II) for counting the droplets in a charged cloud. Since the values obtained were again highly concordant, an incidental verification is afforded for a method used by many investigators in recent years.

It now becomes interesting to see whether on substituting these values in the equation (1) the granular energy comes out the same for grains of different sizes and densities, and (2) the value of Avogadro's constant is in the neighbourhood of 2.72×10^{19} , as indicated by previous researches in many different departments of physics. Five series of observations were made, with grains varying in mass over a range of 1 to 40. In each series many thousands of grains were counted or photographed. The resulting values of the granular energy were in close agreement, thus verifying experimentally the theorem of the

equi-partition of energy among different masses ; and the consequent values of Avogadro's constant ranged from $2.3 \cdot 10^{19}$ to $3.5 \cdot 10^{19}$ with a mean of $3.1 \cdot 10^{19}$ the most probable value from the best series being $3.12 \cdot 10^{19}$.

When it is remembered that before these experiments it might have seemed improbable there should be any change of distribution within the minute height of a few microns studied, and that it was just as likely that all the grains would be found on the bottom of the vessel ; that in the first case the value of Avogadro's constant would have come out zero, and, in the second infinite ; it can hardly be conceived as an accident that the value obtained should be so near that to be expected on other grounds. Thus the molecular theory of the Brownian movement seems to be experimentally established and with it the objective reality of the molecules.

The value for Avogadro's constant finally adopted by Perrin is based on still another series of observations carried out with the utmost precision and covering 13,000 grains. It is $3.15 \cdot 10^{19}$. From this may be deduced the following numbers for comparison with the table on pp. 106, 107.

Number of molecules of any gas, at standard temperature and pressure, per cubic centimetre	...	...	...	$3.15 \cdot 10^{19}$
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Charge of an electron in electro- static units		$4,11 \cdot 10^{-10}$
Mass of hydrogen atom		$1,43 \cdot 10^{-24}$
Mass of electron (1775 times less)		$0,805 \cdot 10^{-27}$
Diameter of hydrogen molecule	...	$2 \cdot 10^{-8}$
Diameter of electron		$\frac{1}{3} \cdot 10^{-12}$

The electron is therefore about three times as small compared with the hydrogen molecule, as the earth is, compared with the diameter of its orbit round the sun !

The results just given are derived from a secondary consequence of the molecular theory of the Brownian movement, viz. the law of distribution of the grains in a vertical column of the liquid. A more direct verification is possible. Although the actual speed of any one grain cannot be determined, owing to the irregularities of its serrated path, Einstein, applying the theory of probabilities, has deduced (1) a formula for the mean displacement of a grain in a given interval, (2) a proof that the actual displacements observed must be distributed about the mean according to Maxwell's law for the distribution of the velocities about the mean velocity, and (3) a formula for the energy of rotation of a grain about any axis, assuming from the 'equipartition of energy' that this will be the same as the mean energy of translation in any direction. All these points were tested.

(1) The actual displacements of sets of 50 to 200 separate grains were noted at intervals of 30 seconds to two minutes. From a comparison of the results of six sets of observations with Einstein's formula, Avogadro's constant came out in close agreement with previous values, $3.19 \cdot 10^{19}$.

(2) The displacements were found to be distributed about the mean in striking agreement with Maxwell's target law.

(3) Although the minute grains employed in these experiments were seen to be rotating, no measures could be made upon them. Naturally, since Einstein's formula indicates that grains of even one whole micron diameter must turn on the average through 100° per second. But with much larger grains, of 13 microns diameter, the mean rotation comes down to 14° per minute. By means of markings on these larger grains the angle turned through per minute could be measured, and the results of 200 observations gave a mean rotation of 14.5° per minute!

The Blue of the Sky.

Avogadro's constant, the number of molecules in a cubic centimetre of gas at standard pressure and temperature, had been estimated within somewhat wide limits from various thermodynamic and other considerations. It could be fixed much more

exactly by various methods (Ch. VII) based on counting the atoms from radium. Thus Rutherford and Geiger obtained the value $2.72 \cdot 10^{19}$; Millikan $2.644 \cdot 10^{19}$. Other values were obtained from the theory of radiation, $3.43 \cdot 10^{19}$ by Lorenz from the distribution of energy in the spectrum, $2.72 \cdot 10^{19}$ by Planck from the radiation of a black body. These are in fair agreement with Perrin's value, $3.15 \cdot 10^{19}$, above.

Still another value may be obtained, from a most unexpected quarter, the blue colour of the sky. Fine dust-particles or water-globules, if near the wave-lengths of light in size, behave quite differently to the short waves of the blue and violet and the longer waves of the red. The blue waves are scattered, *i.e.* reflected in all directions from the particles, just as ripples are reflected from the sides of a block of wood floating in calm water; while the long red waves roll through them unaffected, just as a sea-wave would roll on merely tossing the block as it passed. Helmholtz applied this fact to explain, for instance, the colours of sunrise and sunset. An observer looking down a valley towards the setting sun, receives rays which have travelled a great distance horizontally through the atmosphere. They have consequently lost much of their blue by scattering, and have an excess of red. On looking *across* them at the opposite hills he receives the rays which

are being scattered, and sees the blue haze of distance drawn like a veil across the hills; while from overhead he receives other scattered rays giving the blue of the sky. Even the red of these rays passing overhead may sometimes be seen. For they are bent round by refraction in their long path through the atmosphere at the rim of the earth, as they would be at the edge of a spherical lens, and converge to a point far behind the earth from the sun. During a total lunar eclipse the moon finds herself there, and this 'sifted' light is the only light she receives, since the body of the earth blocks out the direct rays. And hence is she covered during totality by a rosy copper glow.

Lord Rayleigh showed that the molecules of the air are themselves able to scatter light in this way, and from the resulting formulae he was able to deduce limits for the number of molecules per cubic centimetre. Quite recently L. Vessot King¹ has introduced terms into Rayleigh's differential equations which allow for absorption and self-illumination. The solution shows that the theory of molecular scattering can then account for the facts of sky-radiation, and, when compared with observed results, yields values ranging from $2.24 \cdot 10^{19}$ to $2.51 \cdot 10^{19}$ for Avogadro's constant.

That values so consistent should be derived from

¹ *Proc. Roy. Soc.* Nov. 7, 1912.

facts so remote and apparently discrete, points to the deep underlying relation between the various regions of physics, which, though the links cannot yet always be traced in imagination, may even now be expressed in equations between the formulae for Avogadro's constant.

CHAPTER IX

THE NEW ATOM

IN face of the facts we have been recounting the concept of the hard, unchangeable atom needs fundamental revision. Already thirty years ago Rowland of Baltimore, from a consideration of the iron spectrum with its thousands of lines each indicating a definite rate of vibration, was led to remark that compared with an atom of iron a grand piano must be a very simple structure! And now it seems that some atoms can be transmuted with the emission of helium atoms and electrons. Of these, therefore, an atom must in some way be built up. If, as we shall see, the mass of an electron is wholly electrical, its diameter can be shown to be of the order 10^{-13} cm.; that of an atom is 10^{-8} cm. The electron is thus one hundred thousand times smaller than the atom, and the spaces between electrons perhaps one hundred million times the

diameter of an electron. This suggests inevitably an arrangement like a planetary system.

Again, the velocity with which a helium atom is projected from radium *C*, for instance, would require an electric field of more than four million volts to produce it. This is inadmissible, and we are driven to conclude that the atom already possessed this speed before disruption. Once more the planetary system is suggested, the electrons and helium atoms moving about each other with *orbital* velocities, as the planets move round the sun.

Upon these ideas J. J. Thomson has built a very interesting model of an atom. It had been shown by Larmor that an electric charge in motion radiates energy, *if its motion is changing*, i.e. if it is being accelerated, in proportion to the square of its acceleration. A single electron moving in a circular orbit is thus a great radiator, and must soon lose its energy; but Thomson showed that the loss by radiation rapidly diminishes if the number of electrons moving in the circle is increased. Accordingly, as a rough approximation, he worked out the case of an atom consisting of a central positive charge and a number of electrons arranged symmetrically round it in a circle, and moving about it as the planets move round the sun. A model of such a 'Saturnian' atom has interesting analogies with known chemical laws:

1. Not more than a certain number of electrons

can continue in *stable* motion in one ring. If more be added, the system breaks up into two rings, an inner and an outer. As the number is increased, there is another rearrangement in three rings, and so on. Consider now the groups corresponding to 3, 11, 24, 40 and 60 electrons. Each is derived from the preceding group by the addition of an extra ring. For instance, the group of 40 has four rings, of

3, 8, 13, 16 electrons ;

that of 60 has five rings :—

3, 8, 13, 16, 20.

Such atoms, having so much that is common in their constitution, would be expected to show a certain similarity in their properties, and might well correspond to the elements of recurring character which stand at the heads of the vertical columns in Mendeleef's periodic table.

2. The groups may be classified in another way. We may take all those which can exist with an *outer ring of a definite number*. For instance, there are nine possible stable arrangements with an outer ring of 20. The smallest number with such a ring is 59 : the greatest 67. The group of 59 could not lose an electron without breaking up into an entirely new arrangement ; this suggests an inert element of no valency. The group of 60 could only lose one electron

without breaking up, and would be like an electropositive, monovalent element. The group of 61 is more stable and could not so easily lose an electron, but is capable in the end of standing the loss of two. It would thus be divalent and still electropositive, but less so than the group of 60.

At the other end of the series in the group of 67 the outer ring is very stable, but if it acquires another electron, it must become the smallest and least stable of the new series of groups with a larger outer ring. It is more likely to lose the electron again at once, and, like the group of 59, would resemble an inert element of no valency. The group of 66 is the most electronegative of the series, but could only retain one extra electron and is therefore monovalent. The group 65, though less likely to acquire electrons, could retain two, and would be divalent.

It is very suggestive to compare these results with the known characters of such groups of elements as the following:

- (1) *He, Li, Be, B, C, N, O, F, Ne;*
- (2) *Ne, Na, Mg, Al, Si, P, S, Cl, Arg.*

In each of these groups the first and last are elements of no valency; the second and last but one are monovalent but electropositive and electronegative respectively; the third and last but two are divalent, electropositive and electronegative respectively.

From these considerations we may even get a hint of the mechanism of chemical combination. The electrons are less firmly held in the *electropositive* members of each series. When, therefore, a substance with an atom corresponding to an electronegative group is mixed with one which is electropositive, the negative atoms would be apt to gain an electron at the expense of the positive, thus setting up electric forces between the two which might hold them together in permanent union.

3. Lastly, some of the arrangements are stable if the orbital velocity exceeds a certain critical value, but must rearrange themselves if their speed falls below it; just as a spinning top continues 'sleeping' till friction reduces its speed below a certain limit, when it falls over into violent irregular motion.

It is thus, according to Thomson, that the α particles may be shot out from radium. Although in a heavy atom built of many electrons the drain of energy by radiation may be very small yet in course of time the velocities must sink to the critical value, the atom falls into an entirely new arrangement with diminished potential energy, and the energy released may suffice to eject parts of the system with the violence of an explosion.

Another cause for the disruption of an atom has been suggested by Lodge. Electromagnetic theory indicates, as J. J. Thomson showed in 1887, that a

moving charge of electricity acquires a certain inertia, in virtue of its motion, through the grip which the Faraday lines of force travelling with it have upon the ether. It thus resists change of motion as if it had an *electrical mass* independent of any material nucleus on which the charge may reside. This added mass is nearly constant for slow speeds and equal to $\frac{2}{3} \frac{e^2}{a}$,

where e is the charge and a the radius of the sphere on which it is distributed. (It was from this formula that the diameter of an electron was calculated above,

since $a = \frac{2}{3} \frac{e^2}{m} = \frac{2}{3} \cdot \frac{e}{m} \cdot e$, and both $\frac{e}{m}$ and e are known.)

But as the speed of the moving charge increases beyond half the velocity of light, the electrical mass grows rapidly, and theoretically should become infinite when the speed of light itself is attained. Of course this only means that in an ether not subject to disruption the speed of light radiation is the highest that can be obtained.

It has been possible to submit this theory to direct experiment. Radium emits electrons with speeds ranging from one-fifth up to 99·8 per cent. of the velocity of light; and by measuring the ratio $\frac{e}{m}$ for these Kaufmann showed in 1906 that the mass of the electron was at all speeds within less than one per cent. of what it should be according to theory, *if the*

mass is wholly electrical. An electron is thus a disembodied charge without a material nucleus.

Now Lodge points out that the loss of energy by radiation must have the same effect on the revolving electrons in an atom as motion in a resisting medium would have upon the planets. The orbits would slowly contract but *the speed would increase* as they drew closer in to the central body. At last, as the speed of light was approached, the mass of the electrons would begin to grow rapidly, as if, while a flywheel is running near the safety limit, its rim could suddenly be made many times as thick. The result would be explosion and the projection of parts of the system with the high orbital velocities they possessed at the moment.

The α Rays.

Whatever weight be attached to these particular suggestions, the view that the cause of disruption of an atom must be sought in the atom itself is strongly supported by some interesting experiments by Bragg and Klecman on the range of the α particles in air. Using a very shallow testing chamber which could be set at different distances from the radium employed as a source, they obtained a curve showing ionization plotted against distance, with four 'knees' or bends in it. The four parts of the curve correspond to the

four sources of α particles, which are found to have quite definite and different ranges in air before their ionizing power is extinguished. The ionizing power of each particular kind *increases to a maximum as the chamber is removed from the source and then suddenly disappears*. The ranges, which are so characteristic that the source may be identified by the range of the α particles it emits, are as follows :—
for α particles from

radium	3.5 cm.	radium A	4.83 cm.
emanation	4.23 „	radium C	7.06 „

Similar values, characteristic for each source, have now been found for every transformation which emits α particles, and are given in the table on p. 91.

The sharpness with which the ionizing power ceases may be shown to a large audience by a beautiful experiment due to Soddy. A disc rendered active by exposure to radium emanation and left long enough for radium C to develop is placed in the centre of a flask about six inches in diameter, whose inner surface has been dusted with fluorescent zinc-sulphide. No light is seen, for the walls are just beyond the 7 cm. range. But if the air be exhausted from the flask, at the first stroke of the pump the glass shines up brilliantly under the bombardment of the α particles which can now reach it through the rarer air.

The β and γ Rays.

Very interesting sidelights are thrown on this view of the atom in a recent paper by Rutherford¹ on the origin of β and γ rays. We have seen that each atom of an α ray product emits on breaking up a single α ray with definite range and velocity characteristic for the substance, the only exception being thorium C , which emits two α rays for each atom. (*But see* p. 93.)

By analogy it would be natural to expect that one β ray would be emitted for each atom. The general evidence indicates that this is the case. Yet the experiments of Von Baer, Hahn, Meitner and Danysz have shown that the β rays from the same product are by no means homogeneous. When a narrow pencil of β rays is subjected to a magnetic field, it is analysed into a 'spectrum' consisting of many bands each deflected through a different angle, having therefore its own special velocity and energy. Thus the rays from radium B and C together give rise to as many as thirty different bands. Moreover, there is no obvious relation between the intensities of the β rays and the γ rays arising from the same transformation. It would seem, then, that either the same type of atom may break up in many totally different ways, a suggestion improbable in

¹ *Phil. Mag.* Oct. 1912.

itself and negated by the fact that only one type of new product results; or, the β rays are altered in speed after their production and during their escape from the atom.

Now Rutherford has found, from a study of eleven out of the thirty groups of β rays from radium *C*, that the energy in each group falls short of the energy in the swiftest group by a simple multiple of one or other of two quite definite amounts of energy, E_1 and E_2 , or by the sum of such multiples. Can we give a meaning to E_1 and E_2 ? Well, Barkla, it will be remembered, has shown that each element emits one or more definite types of X radiation which are characteristic of it; and a comparison of his formulae with Soddy's experimental results makes it probable that the penetrating γ rays from radium *C* are Barkla's characteristic radiations from radium when excited by the escape of β rays. Now E_2 turns out to be very nearly the calculated energy of β particles required to excite the characteristic radiation from radium *C*. It is possible, though not yet proved, that E_1 may be similarly connected with Barkla's second type of radiations characteristic of radium.

Rutherford therefore conceives the atom, like Thomson, as a positive nucleus (but of very small¹

¹ The nucleus must be small to account for the phenomena of scattering of α particles by matter. On collision with an atom the α particle dives round the nucleus in a hyperbolic orbit, just as non-

dimensions) surrounded by an electronic system probably rotating in rings. Instability, for any cause, of the nucleus may cause the expulsion of an α ray; instability of the electrons may start a β ray. When an electron escapes from a ring near the surface of the atom, it is merely a high-speed β ray emitted without production of γ rays. Radium E and Uranium X are cases in point. But an electron escaping from an inner ring may have to pass, on its way, through rings or regions where it gives rise to γ rays, with a loss of definite amounts of energy characteristic for each ring. This fits well with Bragg's view that β and γ rays are mutually convertible forms of energy, except that apparently a β ray may give rise to several γ rays instead of the single one allowed by Bragg. The same concept is applied by Sir Joseph Thomson in his latest study of the positive rays in a vacuum tube¹. He finds from the photographic curves that atoms may be multiply charged. The hydrogen atom always carries one ionic charge. The majority of the elements have twice the charge, and the mercury atom has been found with as many as eight ionic charges. This suggests that an atom may be ionized in either of two ways :—

recurring comets do in their single visit to the sun. The number of α particles which will be deflected through a given angle on scattering may be calculated by the theory of probabilities, and the results have been verified by Geiger over a wide range of angles.

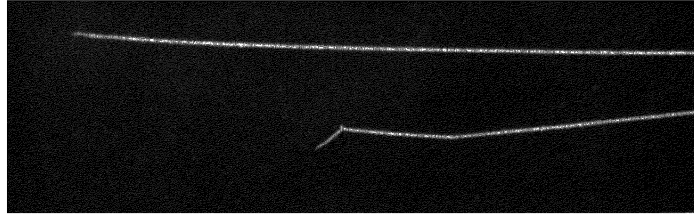
¹ *Phil. Mag.* Oct. 1912.

(1) by collision with a β particle, when an electron may be struck out from the system, or

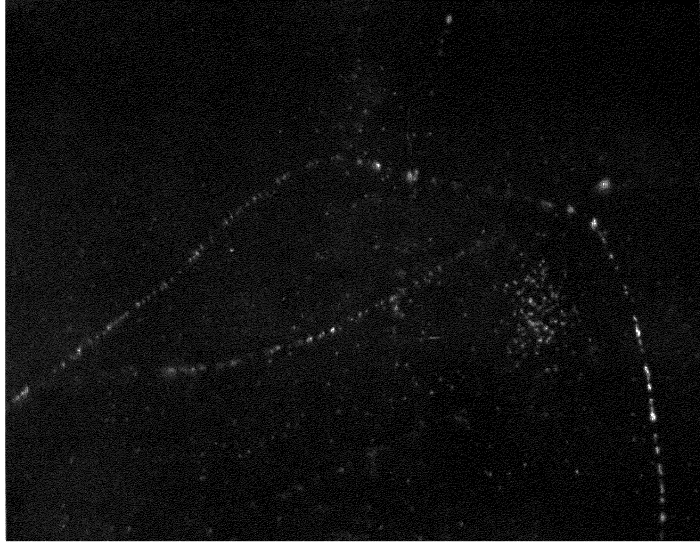
(2) by collision with an atom, when the nucleus runs away from the whole system of electrons, but then regains some.

The strange fact that the ionizing power of an α particle increases as its velocity falls off has been verified directly by experiment, and is perhaps after all only to be expected. We may form a rough idea of what happens, if we regard a β particle, or electron, shot through a molecule as a Mauser rifle bullet of small mass but high speed fired through a window. It cuts a clean hole and removes but a minute piece of glass. The α particle is by comparison a large and lumbering object which shatters the molecule as a brick hurled through the window would shatter the glass. And just as the brick would be more effective the lower its velocity until its speed is just too small to break the glass, so the α particle, always a far more efficient ionizer than the small and speedier electron, will increase in efficiency till suddenly it loses its power altogether¹.

¹ C. T. R. Wilson (*Proc. Roy. Soc. A.* 87, 1912) has actually photographed the trails of both α and β particles, shown by the droplets condensed on the ions produced on their passage. The first photograph (see *Plate*) shows the trails of two α particles. They are continuous, owing to the large number of ions produced; and they are deflected through 10° and 48° respectively by 'single scattering' on collision with an atom. In the second photograph



Track of α Particles



Track of β Particles

That the range should be a fixed property of the source of α particles shows that the initial velocity of discharge is a fixed character, of the atoms disintegrating, not lost even in the act of bursting.

Some consequent experiments by Rutherford showed that when the ionizing power was lost, the photographic and fluorescent properties went with it and yet the speed of the α particles had only been reduced by about 40 per cent. They still retained about one-twentieth of the speed of light. There seems to be, therefore, a critical velocity below which the projected α particles lose the power of producing all the effects by which alone they can be detected¹. J. J. Thomson suggests that when the speed sinks to this critical value the positive α particles can no longer prevent an electron from tacking on to them. They thus become neutral, and henceforth differ in no respect from an ordinary atom of helium.

It is impossible to resist the thought that if this be so, all the known kinds of ordinary matter may be undergoing slow transformations, but that only those which, like the radio-active elements, give rise to

the trails of the β particles are beaded, for only a few ions are produced, strung out along the trails. The writer has to thank Mr Wilson for kindly allowing the use of these photographs.

¹ But Geiger, using the method of Scintillations, has since detected α particles with only .26 of the velocity of α particles from radium C. Though the speed diminishes rapidly towards the end of the path there is no certain evidence of a critical velocity.

the projection of electrons and α particles with more than a certain velocity are open to our detection. This would, indeed, point to an evolution of inanimate matter analogous to that evolution of types which rules in the realm of organized life.

But here is met again the question which led Herschel in the seventies to class the atoms as 'manufactured' articles. Why are there only some hundred distinct types? And how is it that the myriad members of each type resemble each other with such exactitude that an atom of hydrogen, for example, on the confines of the universe can be recognized and identified with its kindred on earth to-day by the momentary quiver it imparted to the ether thousands of years ago? From the point of view just indicated the answer is this. The known elements are but the more stable stages in the universal flux, with a mean life so long that they 'abide our question' by the gross methods of ordinary chemistry. They are in fact, by a further analogy with the evolution of the animate world, the survival of the fittest among the infinitely varying types of matter, the fittest—to *survive*.

But it is time to draw a sharp line between the speculations sketched in this chapter and the solid experimental facts described in those which precede it. We have reached the verge where knowledge is in the making. It is permissible to take a look

forward with the pioneers into the unknown; but safer to get back as soon as may be to established fact. As Leonardo, that wonderful forerunner, said four hundred years ago :

‘Nature never deceives. Only man’s judgment deceives, in promising things not supported by experiment.’

What the next step will be, whether all mass will be proved to be electrical like that of the electron, or whether it be some great simplification by means of a universal concept such as the ether—that makes the interest of the outlook.

Meanwhile, it is certain that in some cases transmutation, the dream of the alchemist, goes slowly but inexorably on, accompanied by the unlocking of vast stores of atomic energy. But by a strange irony the interest has shifted. The alchemist sought to turn the baser to the nobler metals by the sacrifice of energy in the shape of heat, but was impotent to effect the change. His successor of the twentieth century knows that if the transmutation could be effected the metals would be but as dross to the stores of energy set free, but is equally impotent to delay or hasten the change.

The new knowledge gained in the last decade is a true development, not a destructive revolution. Conservation of Energy stands where it did, though unsuspected and enormous stores of atomic energy have

been brought into view. And the Atomic Theory is still the guide of the chemist, though for the purposes of modern physics he has been compelled to look 'beyond the atom,' and in the words of Blake—

‘To see a world in a grain of sand
And a heaven in a flower.
To grasp infinity in the palm of the hand,
And eternity in an hour.’

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