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The Atomic Theory

BY

SIR J. J. THOMSON, O.M.

CAVENDISH PROFESSOR OF EXPERIMENTAL PHYSICS
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THE ATOMIC THEORY

THE theory that matter in spite of its apparent continuity is in reality made up of a great number of very small particles, is as old as the science of Physics itself, and was enunciated almost as soon as men began to reason about physical phenomena. It would, however, be misleading to suppose that there is any very close connexion between the modern Atomic Theory and the views of Democritus and Lucretius. The old theory was in intention and effect metaphysical rather than physical, theological rather than scientific. The physics of two thousand years ago was far too scanty and uncertain to afford any support or test for such a theory; indeed, if I were called upon to prove to you that Democritus was right when he held that matter was discontinuous, and Aristotle wrong when he said it was not so, I should have to appeal to facts not one of which was known either to Democritus or Aristotle. The great and invaluable service which the Greek atomists have rendered to science is that they were the first to attempt on mechanical principles to explain complicated physical phenomena as the result of combinations of simpler ones; they pointed out the goal which science is still struggling to reach. For two thousand years the Atomic Theory itself made no progress, because, though in form a physical theory, it had no real connexion with physical phenomena, no facts were known by which it could be tested, and it was too vague to suggest for itself effects which could be put to the test of experiment. It was sterile because it was divorced from experience. It affords a striking proof that a theory can only grow by the co-operation of thought and facts, and that all that is valuable in a physical theory is not only tested, but in most cases suggested, by the study of physical phenomena. In the interplay between mind and matter in scientific discovery, the parts played by the two are, I think, widely different from those usually assigned to them in popular estimation. There is a widespread belief that the mind itself is desperately speculative, that it is only kept from wild imaginings by the control of its stolid and prosaic partner, the physical facts. The true state of affairs is, I think, that it is the mind which acts as the brake in this combination, that the impulsive partner is the facts, and that these spur on the mind to take leaps which it would shudder at when not under the influence of this stimulus. Nature is far more wonderful and unconventional than anything we can evolve from our inner consciousness. The most far-reaching generalizations which may influence philosophy as well as revolutionize physics, may be suggested, nay, forced on the mind by the discovery of some trivial phenomenon. To take an example, an improvement in the method of exhausting air from closed vessels enabled experimenters to send an electric discharge through gas more highly rarified than had previously been possible. When they did this they observed that the glass of the vessel shone with a peculiar phosphorescent light: the study of this light led to the discovery of cathode rays, cathode rays led on to Röntgen rays, and the study of those rays started ideas which have entirely changed our conceptions of matter.

As facts play such a large part in stimulating our imagination and suggesting new ideas, every mechanical improvement in our apparatus, every new method which makes it easier to investigate physical phenomena, affects not merely the technique of the science, but may originate ideas which will ultimately revolutionize our philosophy of the universe. I feel sure, for example, that many of the ideas we now possess regarding atoms and their structure originated in the study of phenomena which would not have been discovered but for Sir James Dewar's invention for producing very high vacua by means of charcoal cooled by liquid air.

It is not to the theorist alone that scientific ideas owe their origin; the inventor of a new piece of apparatus, the mechanic whose skill enables him to construct the exceedingly sensitive instruments which detect effects so small that they would escape a coarser measure, all play their part in the progress of scientific ideas.

It is often assumed that the mechanical arts minister to nothing but material wants, that telephones and telegraphs, motor-cars and aeroplanes merely make life more luxurious or exciting; they may do this, but the engineering skill and activity of which they are the symbol have other and more intellectual effects, and, by the aid they afford us in investigating material phenomena, may profoundly affect the most philosophical and abstract science.

To return, however, to the Atomic Theory: it is not until the seventeenth century that we find any serious use was made of it for the explanation of physical phenomena, and to that great philosopher, Robert Boyle, who was so closely connected with Oxford, belongs the credit of being the first to use the theory in a way at all analogous to the methods of modern physics. Indeed Boyle's point of view is quite surprisingly modern. Newton gave the theory his powerful support, and taught that cohesion and chemical affinity were the manifestations of forces between the atoms. One feels, however, that these great men regarded the idea of atoms as too vague and speculative to be called upon, except as a last resort: and though Voltaire at the end of the eighteenth century could summarize the state of opinion by saying: 'bodies the most hard are looked upon as full of holes like sieves, and in fact this is what they are. Atoms are accepted indivisible and unchangeable,' it was not until 1801, the date of Dalton's *Atomic Theory*, that the conception of the atom played any considerable part in scientific discovery. Dalton's theory was based on the proportions by weight of the different elements in various chemical compounds; he showed that these proportions are exactly those which would exist if each element consisted of a great number of particles, all the particles of any one element being exactly alike, but each element having its own particular kind of particle. He determined the relative weights of the atoms of a number of chemical elements, and he supposed that compound bodies were formed by the union of one or more particles of one element with one or more particles of other elements.

This view gave such a clear-cut and tangible representation of chemical combination, that it was very largely, though not universally, adopted, and caused the conception of the atom to be familiar to every chemist.

Dalton traced the atoms of the different elements in all their migrations from one compound to another by means of their weight; this was a quality they could neither change nor disguise; until quite recently, however, this was about the only quality of the atom of which this could be said. Indeed, with many qualities the way the individuality of the atom is disguised is exceedingly remarkable, and sceptics had perhaps some excuse when they failed to recognize the atom through all its migrations. Thus a meal of bread and water contains exactly the same kind of atoms as a draught of a solution of prussic acid ; by merely mixing two colourless liquids we can get another showing the most vivid colour ; iron is intensely magnetic, so are many of its salts ; there are others however which, as Professor Townsend has shown, are non-magnetic, while some of those interesting compounds of iron and carbon monoxide are actually diamagnetic. Does the atom then preserve nothing intact as it goes from one compound to another except its weight ? We now know that it does, and we can now give convincing proof of the individuality of the atom throughout migration. The visible light which the atom emits changes with the compound, yet, as Professor Barkla has shown, an atom besides this visible light can also emit that peculiar kind of invisible light called Röntgen rays, which only differs from ordinary light in the kind of way that blue light differs from red. Barkla has shown that each kind of atom emits a peculiar type of Röntgen ray, which remains unaltered, whatever kind of partner the atom may have. Thus we can detect the presence of iron, say, in any compound, by studying the Röntgen rays emitted by that compound ; if it contains iron we shall find the characteristic Röntgen radiation of iron present, however complex the compound may be. With such penetrating agents as Röntgen and cathode rays at our disposal, other properties which the atom retains unaltered have been brought to light, such, for example, as the absorption of these rays when they pass through atoms ; the absorption by a given atom is quite independent of any other atoms with which it may happen to be associated, and depends only on the quality of the atom itself.

The properties of the atom may thus be divided into two classes; in one class we have the properties, such as its weight and its Röntgen radiation, which are intrinsic to the atom, and which it carries with it unchanged into any compound of which it may be a constituent; in the other class we have the properties, such as the chemical properties of the atom, which depend upon its environment and upon the physical conditions, such as temperature, to which it is subjected. From the point of view of the structure of the atom, the properties of the second class depend upon the conditions of the surface of the atom; close to the surface there are small negatively electrified particles, which can be detached from the atom by agents at our disposal, and the properties of the atom modified thereby: the properties of the first class depend upon the structure of the innermost parts of the atom where there are also these negatively electrified particles, which are, however, so firmly held that they are not loosened by any chemical treatment it is in our power to apply to the atom.

For some time after Dalton's enunciation of his theory, no very important advances were made in our knowledge of atoms, but in the second half of the nineteenth century the Atomic Theory was greatly advanced by the work of Clausius, Clerk-Maxwell, Boltzmann, Joule, Kelvin, and Willard-Gibbs on the Kinetic Theory of Gases. These philosophers showed that many of the properties of gases can be explained on dynamical principles if the gas is regarded as a collection of a very large number of small particles in rapid motion. Though some important results as to the size of atoms were obtained in this way, the greater part of the work related to the properties of swarms of atoms, and threw but little light on the constitution of the individual atom. In fact, it was not until quite the close of the nineteenth century, when attention was turned to the study of electrified atoms instead of unelectrified ones, that our acquaintance with the atom became at all intimate. The advance made through the electrification of the atom has been most remarkable; it is due to the fact that an unelectrified atom is so elusive that unless more than a million million are present we have no means sufficiently sensitive to detect them, or, to put it in another way, unless we had a better test for a man than we have for an unelectrified molecule, we should be unable to find out that the earth was inhabited. The electrified atom or molecule, on the other hand, is much more assertive, so much so that it has been found possible in some cases to detect the presence of a single electrified atom; a billion unelectrified atoms may escape our observation, whereas a dozen or so electrified ones are detected without difficulty.

One reason why electrified atoms and molecules are so much easier to study is that we can subject them to forces far more intense than any we can apply to unelectrified ones; we can exert much more control over them, and force them into situations where their habits may be observed. For example, if a mixture of different kinds of electrified atoms is moving along in one stream, then when electric and magnetic forces are applied to the stream simultaneously, the different kinds of atoms are sorted out, and the original stream is divided up into a number of smaller streams separated from each other. The particles in any one of the smaller streams are all of the same kind.

Thus, if the original stream contained a mixture of hydrogen and oxygen atoms, it would, by the action of the electric and magnetic forces, be split up into two separate streams, one of which consisted exclusively of oxygen, the other of hydrogen atoms ; we shall call the streams into which the original stream is split up the electric spectrum of the atoms, and we can by means of it analyse a stream of atoms, just as a beam of light is analysed by sending it through a spectroscope and observing the different rays into which it is divided.

By means of the electric spectrum we can prove in a very direct and striking way some of the fundamental truths of the Atomic Theory. For example, when we form the electric spectrum of a mixture of gases, such as the air, we get a limited number of sharply-divided streams, which show no tendency to merge into each other. This shows that the gas contains only a few kinds of particles, and that all the particles of one kind have exactly the same mass, for if there had been any variation in the masses the streams would have been fuzzy. This shows that all the atoms of an element are alike ; this had sometimes been questioned, and it had been suggested that there might be considerable variations in the masses of the atoms of the same element ; ordinary chemical analysis could not settle this question, for it gives nothing more than the average mass of billions of atoms. The electric spectrum can be applied to prove the existence of molecules as well as of atoms, for when we take the electric spectrum of pure hydrogen, for example, we find that we get two streams, and that the mass of the particles in one stream is twice that of those in the other ; thus the heavier particles consist of two of the lighter ones, and in hydrogen there must be some systems with two atoms, others with one. In the majority of gases the spectrum consists of two streams ; there are however some gases, such as helium and mercury vapour, where there is only one stream instead of two, showing that in these gases we have atoms but no molecules.

Electrons.

But when we analyse in this way a gas through which an electric discharge is passing, we find along with the atoms and molecules particles of an altogether different type; these particles are always charged with negative electricity, and their mass is an exceedingly small fraction, 1/1700, of that of the smallest atom known, the atom of hydrogen. They are so small that their volume bears to that of the atom much the same proportion as that between a small pellet and this room. These particles are called electrons or corpuscles, and no matter what the nature of the gas may be, whether it is hydrogen, helium, or mercury vapour, the electrons or corpuscles remain unchanged in quality; in fact, there is only one kind of electron, and we can get it out of every kind of matter. The conclusion is irresistible that the electron or corpuscle is a constituent of every atom, and that we are able, by forces which we have even now at our command, to detach it from the atom.

Though the electrons were first detected under the somewhat artificial and sophisticated condition of a rarified gas traversed by an electric current, yet, as so often happens in such cases when once they had been detected, they were found to be of quite common occurrence, and to occur in many familiar phenomena. They are found, for example, round a red-hot piece of metal, the filament of an electric lamp gives out large quantities; they come out of metals, whether hot or cold, when these are reflecting ultra-violet light; they are given out spontaneously by radio-active substances; and Haber has described experiments which indicate that they are given out during some chemical reactions. There are, however, many chemical reactions which are not accompanied by any emission of electrons. Whatever the source of the electrons may be, they are always the same; some may be moving faster than the others, but that is the only difference. By observing the behaviour of the electron under electric and magnetic forces, the values of its mass and electric charge—the quantities which determine its behaviour under specified conditions—have been measured; indeed, though the electron has only lately come under our notice, we know a good deal more about it than we do of many things which have been discovered centuries ago. One important result of these measurements is that the electron or corpuscle is of the same type when it is ejected with enormous velocities from radio-active substances, as when it oozes out of a hot body; this is very strong evidence that it cannot be broken up by any forces we can apply, as these would be insignificant in comparison with those called into play when it is ejected from radium. Since the electron can be got from all the chemical elements, we may conclude that electrons are a constituent of all atoms. We have thus made the first step towards a knowledge of the structure of the atom and towards the goal towards which since the time of Prout many chemists have been striving, the proof that the atoms of the chemical elements are all built up of simpler atoms—primordial atoms, as they have been called.

As we have proved that the atoms contain these electrons, the next step is to find out how many there are in any particular kind of atom. This was first done by the following method. When Röntgen rays fall on an electron, the rays are scattered just as light is scattered by the small particles of carbon in the smoke from a peat fire, or by the molecules of air in the upper regions of the atmosphere producing the blue of the sky; this, by the way, has been used to measure the number of air molecules in the sky. Now when we know the mass and charge on an electron we can calculate the amount of hard Röntgen rays scattered by a single electron. Then if we measure the scattering due to the electrons in an atom, or in a million atoms, we shall be able to deduce the number of electrons in the atom. Measurements of the scattering of Röntgen rays were first made by Barkla, and from his results it follows that the number of electrons in an atom is roughly proportional to the atomic weight, and that the actual number is not very far from half the atomic weight; thus in the carbon atom there would be six electrons, in the oxygen atom eight, and so on, while in the lightest atom, hydrogen, there is probably only one. This is a most interesting result when we remember that there is room for 1,700 of these corpuscles in an atom of hydrogen, and that one of the spectra of hydrogen is of exceptional complexity.

Sir Ernest Rutherford by an entirely different method found that the quantity of positive electricity in an atom of atomic weight A is equal to the quantity of negative electricity in A/2 electrons. This also proves that the number of electrons in an atom is half the atomic weight.

The atomic weights of a great many elements are not divisible by two, so that the number of electrons in the atoms cannot be exactly equal to half the atomic weight. As the average difference between the atomic weights of successive elements is about 2, one-half the atomic weight of an element is not very far from its place in the list of elements arranged in order of the atomic weights; this place is called the atomic number of the element. Mr. van Broek has suggested that the number of electrons in an element is equal to its atomic number, and this view is strongly supported by some remarkably interesting experiments made by Mr. Moseley. If we could be sure that we had a complete list of the elements, that few, if any, had escaped the vigilance of the chemist, and that all the elements were members of one family, the atomic number would be the quantity with which we should naturally connect the number of electrons in the atom: for we may regard each element as derived from the preceding one by the addition of a primordial atom containing one electron. There may, however, be more than one family of elements, the successive members in each family growing by a common unit, though the members of one family cannot be changed into those of the other by the addition or subtraction of this unit. I think there are reasons for believing that there are two families of elements; for if there were only one family we should expect that the atomic weight of the lighter elements would increase by a common difference. This is not so. If, however, we divide the lighter elements into two families, those with even and those with odd atomic weights, we find that in each of these families the atomic weights do, with very few exceptions, increase by the common difference 4, and that in fact we get much greater simplicity and order when we arrange them in two series than when we regard them as successive members of a single series. This is illustrated by the following table, which contains the elements whose atomic weight is not greater than 40:

He	4	Li	7
Be	9	B	11
C	12	N	14
O	16	F	19
Ne	20	Na	23
Mg	24	Al	27

Si	28	P	31
S	32	Cl	35
Ar	40	K	39

The differences in the atomic weights are the same in the two series, so that each series may be supposed to grow by the addition of the same kind of primordial atom, but one series starts from one kind of atom, the other from another. The question is, should we not expect the number of electrons in the atom of an element to be connected with the number which represents the order of the element in the series to which it belongs when the elements are divided into two series, rather than with its order in a series which contains the whole of the elements without any rearrangement? As a matter of fact the difference between the numbers given by these views for the electrons in an atom of one of the heavier elements would be too small to be detected by any experiment at present within our powers. With the lighter elements, however, it ought to be possible to distinguish between these views, and experiments with this object are at present being made in the Cavendish Laboratory.

The number of electrons in an atom is such a fundamental quantity that its determination throws a good deal of light on some of the most keenly discussed problems in Physics and Chemistry, such as the transmutation of the elements and the relation between mass and weight. Let us begin by considering its connexion with the first of these questions.

Transmutation of the Elements

The constant difference between the number of electrons in the atom of one element and that in the atom of the element next in the series is strong evidence in favour of the view that the atoms of the consecutive elements differ from each other by the addition of a primordial atom, which apparently is the atom of helium. But though the number of electrons in the atom apparently increases with perfect regularity, the mass of the atom, at any rate in the case of the heavier elements, does not do so. Thus the addition of a constant primordial atom does not produce a constant increase in the mass; there must, therefore, be a change in mass when the primordial atoms coalesce to form the atom of a chemical element; and from the values of the atomic weights of the elements we can get an indication of the change in mass which has occurred. The consideration of this point leads to some very interesting results. It is entirely in accordance with electrical principles that some change in mass should occur when these primordial atoms coalesce; we know, for example, that when we push two similarly electrified bodies together against their mutual repulsion, the mass of the two increases by an amount proportional to the work done in pushing them together. When we know the work spent or liberated in any change of condition, we can calculate the consequent increase or decrease in mass. In chemical combination heat is liberated, and there is, therefore, a change in mass, but a calculation shows that even in the cases when the greatest amount of heat is produced, as for example in the burning of coal, the change in mass is too small to be detected by our most sensitive balances, and though some chemists have devoted a lifetime to the investigation, no change in mass has ever been established as the result of chemical combination. Since the atomic weights of the elements show that in their formation a measurable change of mass has taken place, the changes of energy involved in the formation of the elements must be enormous compared with those liberated in any chemical changes with which we are acquainted. Let us take an example: the atomic weight of chlorine is 35·5; this is not a whole number, it differs from the nearest by half a unit; it follows, therefore, that in the formation of 35·5 grammes of chlorine there must have been a change of mass of at least half a gramme. This involves the liberation or absorption of an amount of energy equal to that possessed by half a gramme moving with the velocity of light, i.e. $2{\cdot}25 \times 10^{20}$ ergs. This is about the amount of work required to keep the *Mauretania* going at full speed for a week, and must have been stored up or liberated from 35·5 grammes, or about an ounce of chlorine. We see that changes in the atom large enough to change the chemical character of the atom, i.e. to split an atom of one element up into different kinds of atoms, involve enormous transformations of energy; in fact the explosion of the atom in a few pounds of material might be sufficient to shatter a continent. We are living in the midst, nay, are made up of quiescent volcanoes; fortunately their slumbers are very sound.

Can we break up the atoms by physical means?

The amount of energy required to break up an atom has a very important bearing on the problem of splitting up the atom, in other words the transmutation of the elements by physical means. We know that the atoms of the radio-active elements break up spontaneously, and give rise to atoms of another kind. Thus radium emanation splits up into helium and radium A, and radium A again splits up. No one, however, has yet been able to influence the rate at which these transformations take place by any kind of physical treatment. Intense heat or pressure, and—what is much more remarkable—bombardment by the α rays given out by the radio-active

Failure to transmute elements.

bodies themselves, seem quite without influence on the disintegration of the radio-active elements. The bombardment by α rays seems to be the most promising means of producing atomic transformation, for in this case the energy of the rays comes from these transformations themselves—‘ ’tis its own pinion that impels the steel.’ They do not, however, appear to produce any appreciable effect, for the life of a radio-active substance in a dilute solution, where it is only exposed to a few α rays, seems to be no longer than the life in a strong solution, where the substance is bombarded by many rays. I have made many experiments to see if I could split up atoms of one kind into those of another by exposing them to electric discharges, bombardment by cathode or positive rays, and other agents ; using the very sensitive method of positive ray analysis to detect the formation of any disintegration products ; this method can detect less than a millionth of a cubic centimetre of a gas at atmospheric pressure. By these means I have been able to disintegrate the atoms to the extent that I could split off from them some of the electrons they contained ; from the atom of mercury, for example, I have been able to detach eight electrons, from hydrogen one electron, the only one it had. I have never, however, been able to get any evidence that I regard as at all conclusive that the atom of one element could by such means be changed into an atom of a different kind ; in other words, that by such means we could produce a transmutation of the elements.

Ratio of Mass to Weight

We have seen that the view, so strongly supported by recent experiments, that the atoms of the elements are aggregations of simpler systems, involves the admission that losses or gains of mass or weight must occur in the formation of the heavier atoms. But we know that the ratio of mass to weight is the same for all substances, from hydrogen, the lightest, up to uranium, the heaviest, and even, as Southern's experiments on uranium and my own on radium have shown, for radio-active substances. Now in the formation of the heavier atoms alterations in mass must have occurred; in spite of this the ratio of weight to mass has not been altered. As enormous changes in energy are involved in changes of mass of the size we are considering—far greater than any we can produce by processes we can use in the laboratory—this is about the severest conceivable test to which we can put the constancy of the ratio of mass to weight; that it can stand it is a result of fundamental importance in the theory of gravitation.

We may ask, does this remarkable constancy in the ratio of mass to weight, which holds in the case of all known atoms, hold also for the very much smaller particles, the electrons? Have these minute negatively electrified bodies any weight at all, or is, as might be expected on one of the electrical theories of gravitation, their weight abnormally large in comparison with their mass? It is perhaps beyond our powers to weigh these particles, but it is not so hopelessly beyond but that, with the improvements in technique which we may reasonably expect as the result of experience, we may entertain hopes of being able to do so before very many years have elapsed.

In the case of the lighter elements, where the changes in mass accompanying the formation of the atom may reasonably be expected to be small, we may take the nearest integer to represent what the mass would have been if there had been no change on aggregation. Taking hydrogen as the unit, the atomic weights of nearly all the elements up to potassium fall just short of whole numbers; this indicates that there has been a diminution of mass in the evolution of these elements. A diminution of mass means a liberation of energy proportional to it, so that the amount of energy liberated in the formation of these lighter elements will be proportional to the defect of this atomic weight from the nearest integer.

Of the lighter elements whose atomic weights have been determined with great accuracy, magnesium and silicon seem to be the only ones where there are indications of an increase of mass, and in this case the increase is so slight that a very small error in the determination of the atomic weight would account for these apparent exceptions.

There are indications that some radical change in the way in which the atom is built up from the primordial atom occurs when we get to atomic weights about 40 or thereabouts. Up to this stage the atomic weights are expressed by very simple numerical relations which fail for the heavier elements; it is at this stage too that on Mendeléeff's system it is necessary to change from the short period of eight elements, which was sufficient to represent the cycle of properties of the lighter elements, to the larger one of sixteen elements to represent those of the heavier ones.

One of the most interesting results of the determination of the number of electrons in the atoms is the simplicity from one point of view of the hydrogen atom, in which there is only one negative electron. Thus, this atom is made up of an electron and the equivalent positive charge. Looked at from this point of view, the hydrogen atom is a very simple structure, in fact the simplest that could be built up of electrons and positive electricity; so that if the atoms of all elements are made up of these constituents there is no room for the existence of an atom lighter than hydrogen, such as that which has sometimes been suspected to exist in the sun's corona. The properties of hydrogen are well known and show no very exceptional simplicity; thus, for example, one of its spectra—the second spectrum—is so complicated that many thousand different lines have been detected, and apparently there is no simple relation between the frequencies of the lines to indicate that they are the members of a single series like the lines in the first spectrum. Is it likely, it may be urged, that such a simple structure as a single electron and one positive charge could give rise to a complication as great as this? But is the system so very simple after all? We must distinguish between arithmetical and physical simplicity. The electron and the positive charge produce an electric field all round them, and an electric field is probably a very complicated piece of mechanism. We may picture it in this case as consisting of a large number of lines of force, with one end on the electron and the other on the positive charge, spreading out into the space round the atom, and we may also suppose that these lines of force may move about even though their ends are at rest, and thus vibrate independently of the electrons. We can easily realize that a bundle of lines of force of this kind could vibrate in a very great number of ways, far more than would be necessary to account for the most complicated spectrum yet observed.

Before we can get very far in explaining the structure of the atom, we shall, I am convinced, have to deal with the question of the structure of the electric field.

It is, I think, possible that an atom may be able to give out vibrations of almost any period if these are excited in the proper way, say by the impact of cathode rays possessing a suitable amount of energy, and that the lines which are actually observed in the spectrum of an element may be determined by the energy which can be given to the electrons, which are sucked into the atom by the attraction the atom exerts upon them, rather than by the inability of the atom to vibrate in other periods. We may compare an atom to an orchestra with a complete set of instruments; the notes given out will depend upon the players as well as upon the instruments, and the absence of certain notes may be due to the absence of the appropriate players, and not to that of the appropriate instrument.

On this view almost any vibration could be excited if the atom were bombarded with cathode rays of suitable energy, and the vibrations in the visible spectrum are to be regarded as excited by the impact of cathode rays in much the same way as Röntgen rays are excited in a discharge tube, the difference being merely that the cathode particles which excite the Röntgen rays have much more energy than those required to excite the rays in the visible spectrum,—that in fact, in the way it is produced, as well as in its physical nature, visible light is a special type of Röntgen ray.

We can produce a system which is still simpler than the ordinary hydrogen atom, for we can extract the electron from the atom and get merely the positive charge left: these positively charged hydrogen atoms exist in large numbers in the positive rays. The hydrogen atom, minus its electron, is the simplest atom we can conceive; it is much simpler than the normal hydrogen atom, with its electron intact, and essentially different from it. The investigation of its properties is a matter of very great interest. The comparison of the spectrum of a hydrogen atom which has lost its electron with that of one which has not, is a matter of very great importance; unfortunately it is extremely difficult to do it in a way which is free from ambiguity. On the view just given, the spectrum should be quite different; indeed we should hardly expect the atom when deprived of its electron to be able to give out any lines in the visible part of the spectrum. I have recently been able to show that when these positively charged atoms impinge on other atoms, they give rise to Röntgen rays; it will be interesting to compare the quality of these rays with those given out by the impact of cathode rays moving either with the same velocity or with the same energy.

The Structure of the Atom

We have seen that each atom contains a definite number of electrons, the number ranging from one for the hydrogen atom to over a hundred for the atom of thorium. The problem of deducing by mathematical consideration the way in which a number of electrons would arrange themselves when in stable equilibrium is one of fundamental importance. In our theoretical investigations of the structure of the atom it is well to keep constantly in our minds the question of the validity of applying to the problem of the individual atom principles which have been established by the study of the properties of collections of vast quantities of atoms. In the atom we have to deal with the electron and the corresponding charge of positive electricity; these are the units of which all electrical charges are built up. The laws of electric and magnetic action which we use in our theoretical investigations are based on the results of experiments, made not with a single unit of electricity, but with collections of millions of such units;

they represent in fact the average effect of millions of individuals. When, however, we come to the atom, we have to deal with the effects produced by the individual electron or positive charge, and not with the average effect produced by countless numbers of such charges. Now it may be or it may not be that the average effect is identical with that produced by each individual, and it may be or it may not be that a knowledge of the average is sufficient to solve the problem of the individual. The statistician is content to know that the average height of male adults is, say, 5 feet 6 inches, and their waist measurement 3 feet, but it is evident that such knowledge would be a very unsatisfactory equipment for one's tailor. Now the laws of electricity and magnetism as stated in our text-books are statistical laws, and when we come to apply them to the atom we are somewhat in the position of a tailor attempting to fit an individual with nothing but a knowledge of the average dimensions of the whole population to go upon. We must, therefore, proceed in a somewhat tentative fashion, and try if our statistical knowledge, which is all we have at present, will ensure a fit for the atom; we need not, however, be very much surprised if the fit is not perfect, and we must, by the means which fortunately are now at our disposal for the study of the properties of the electron and the positive charge, endeavour to supplement our statistical knowledge by the knowledge of the effect produced by each individual. I think that the most pressing need at this stage of the Atomic Theory is the exploration by experiment of the distribution of electrons in the atom; when we know this distribution we may be able to see how we must modify the accepted laws of electrical action to make them applicable to these small charges.

We may, I think, get a useful lesson by considering for a moment from this point of view a theory of the atom which, though it is not in very close touch with physical phenomena, has yet the advantage of being so precisely defined that the properties of its atoms can be deduced by purely mathematical principles. The theory to which I allude is that known as the 'Vortex Atom Theory of Matter', which supposes that the Universe consists of an ideal substance known to mathematicians as a perfect fluid. Some portions of this are supposed to be rotating, the rest not: the rotating parts of the fluid on this theory are the atoms. It can be shown that any portion of this fluid which once possesses rotatory motion will never lose it, while if it does not at any instant possess it, it can never acquire it; the atoms on this theory possess at any rate some of the characteristics of real atoms, as they can neither be created nor destroyed. The atoms of one substance on this theory are differentiated from those of another, not merely by the quantity of the rotating liquid, but also by the speed with which it is rotating. The product of the angular velocity of rotation and the area of the cross section of the rotating fluid is called the 'strength' of the atom; it does not change, whatever vicissitudes the atom may experience, and, along with the volume of the rotating fluid, determines the property of the atom. Now let us consider some of the properties of the individual atoms in this theory, remembering that if we took a collection of a large number of them, the properties of the aggregate would be those of ordinary matter. The effective mass of one of these atoms would change when it came into collision with another atom; this is because the rotating portion of the atom has to drag along with itself a considerable volume of the liquid which is not rotating, so that the effective mass of the atom is the mass of the rotating portion, plus the mass of the liquid thus dragged along with it, and as some of this liquid may be detached from or added to the atom when it comes into collision with another atom, the effective mass of the atom will be changed by the collision. For the same reason, the effective mass of the atom changes with its velocity—the greater the velocity the smaller being the mass; so much is this the case that we have the paradoxical result that the momentum of the atom decreases as its velocity increases, and that the more slowly the atom moves the greater is the kinetic energy. Again, if all the atoms were made of vortices of the same 'strength', we should find that certain mechanical quantities would all be integral multiples of a definite unit, i. e. these dynamical quantities, though not matter, would yet resemble matter in having an atomic constitution, being built up of separate indivisible units. The quantity known as 'circulation' would have this property; it would always be an integral multiple of a definite unit, and would thus change by abrupt steps, and not continuously. When a particle describes a circular orbit the 'circulation' is proportional to its moment of momentum, and we see that in a theory of this kind the moment of momentum of particles describing circular orbits would always be an integral multiple of a definite unit. We see from this example that when we have a structure as fine as that associated with atoms, we may find dynamical quantities such as moment of momentum, or it may be kinetic energy, assuming the atomic quality and increasing or decreasing discontinuously by finite jumps. In one form of a theory which has rendered great service to physical science—I mean Planck's theory of the 'quantum'—the changes from radiant to kinetic energy are supposed to occur not continuously, but by definite steps, as would inevitably be the case if the energy were atomic in structure. I have introduced this illustration from the vortex atom theory of matter, for the purpose of showing that when we have a structure as fine as that of atoms we may, without any alteration in the laws of dynamics, get discontinuities in various dynamical quantities, which will give them the atomic quality. In some cases it may be that the most important effect of the fineness of the atomic structure will be the production of this atomic quality in some dynamical quantity such as the kinetic energy. If then we postulate the existence of this property for the energy, it may serve as the equivalent of a detailed consideration of this structure itself. Thus, for many purposes (for example, in the elucidation of the remarkable results obtained by Professor Nernst and his pupils on specific heats at low temperatures, or Mr. Bohr's researches on the distribution of lines in various spectra) Planck's quantum theory serves as the equivalent of a knowledge of the structure of the atom.

If we assume that the recognized laws of electrical action hold for the small charges carried by the electrified parts of the atom—the electrons and the corresponding positive charges—we can by the aid of mathematical analysis get some idea of the way in which a number of electrons will arrange themselves when in stable equilibrium. We find that in a symmetrical atom only a limited number of such electrons can be in equilibrium when arranged on a single spherical surface concentric with the atom: the actual number which can be arranged in this way depends on the distribution of positive electricity in the inside of the atom. When the number of electrons exceeds this critical number, the electrons break up into two or more groups arranged in a series

Onion-theory of composition of atom (cp. 8) — social & individual qualities.

of concentric shells. This leads us to the view that the electrons in an atom, if they exceed a certain number, are divided up into groups, into a series of spherical layers, like the coatings of an onion, separated from each other by finite distances, the number of such layers depending upon the number of electrons in the atom, and thus upon its atomic weight.

The electrons in the outside layer will be held in their places less firmly than those in the inner layers; they are more mobile, and will arrange themselves more easily under the forces exerted upon them by other atoms. As the forces which one atom exerts on another depend on the rearrangement of the electrons in the atom, the forces which a neutral atom exerts on other atoms—what we may call the social quantities of the atom—will depend mainly on the outer belt of electrons. Now these forces are the origin of chemical affinity, and of such physical phenomena as surface tension, cohesion, intrinsic pressure, viscosity, ionising power, in fact of by far the most important properties of the atom; and the most interesting part of the atom is the outside belt of electrons. As this belt will be pulled about and distorted by the proximity of other atoms, we should expect that the properties depending on this outer layer of the electrons would not be carried unchanged by an atom through all its compounds with other elements; they will depend upon the kind of atom with which this atom is associated in these compounds; they will be what the chemists call constitutive, and not intrinsic. On the other hand the electrons in the strata nearer the centre of the atom will be much more firmly held; they will require the expenditure of much more work to remove them from the atom, and will be but little affected by the presence of other atoms, so that such properties as depend upon these inner electrons will be carried unchanged by the atom into its chemical compounds. The properties of the real atom are in accordance with these suggestions. By far the larger number of the properties of the atom are of the constitutive type which we have associated with the outer belt of electrons. There are, however, as we have seen, other properties of the atom which are intrinsic to it; these we associate with the inner layer of electrons.

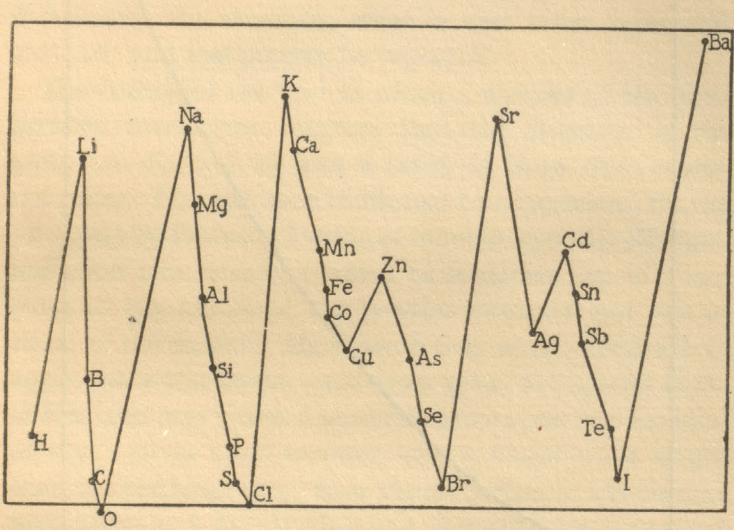

FIG. 1.

The relation between these two types of properties and the atomic weights are very different. The first type, that depending on the outer layer of electrons, waxes and wanes as we proceed along the list of elements in the order of their atomic weights; this is illustrated by the curve in Fig. 1, which represents the variation with the atomic weight of the heat of combination of the element with chlorine. The relation between an intrinsic property of the atom and its atomic weight is a much simpler one, and is of the kind shown by the curve in Fig. 2, which represents, according to the experiments of Mr. Whiddington, the relation between the energy required by cathode rays to excite the characteristic Röntgen radiation of an atom and its atomic weight; the same curve will, from the results of the experiments of Mr. Moseley and Mr. Darwin, represent

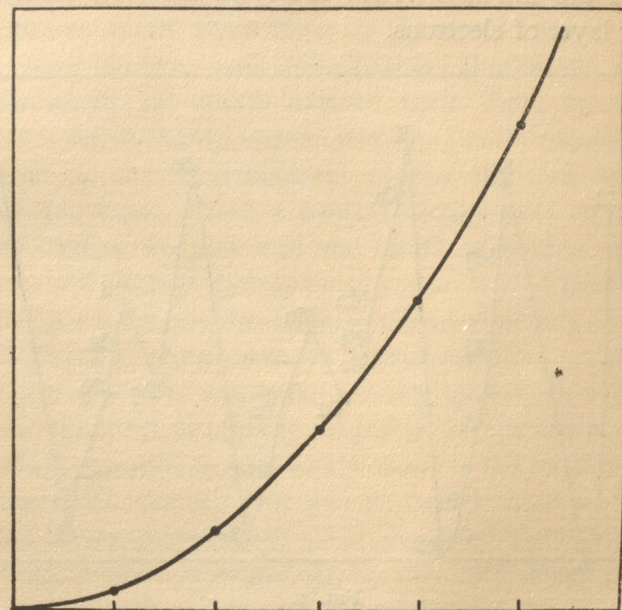

FIG. 2.

the relation between the frequency of the characteristic radiation and the atomic weight. The constitutive properties vary in a quasi-periodic and fluctuating way with the atomic weight, while the intrinsic ones steadily increase or decrease, as the atomic weight increases. This is what we should have expected after our consideration of the properties of groups of electrons when in stable equilibrium. We have seen that there cannot be more than a certain number of electrons in any one layer. Consider how the atom will change as we gradually increase its population of electrons; the number in the outer layer will at first increase, but when it has reached the critical number no more can be added to it; any new added to the atom will now begin to form a new outer layer, the old outer layer becoming an inner one. With the addition of more electrons the same process will be repeated; the new outer layer will absorb electrons until it becomes too crowded, when a new outer layer will split off, and the process be repeated.

The theory of the way in which a number of electrons arrange themselves suggests that the electrons in the atom are divided up into a series of rings, one outside the other. This has been confirmed by experiment, for the discovery by Professor Barkla of the characteristic Röntgen radiation has already enabled us to detect two of these rings in the atoms of the heavier elements and one in those of the lighter. He showed that when submitted to appropriate treatment, each atom gives out special kinds of Röntgen rays; thus a platinum atom gives out one kind of ray, a silver atom another, with a longer wave length than the platinum one. Now the properties of the hardest rays given out by the different elements are connected in a very simple way with the atomic weight; thus Mr. Whiddington showed that the speed of the slowest cathode particle which could excite these rays is proportional to the atomic weight, and Mr. Moseley has shown that the frequency of the vibration is proportional to the square of the atomic number; as this number is roughly proportional to the atomic weight, the one relation would follow from the other by Planck's law. This simple connexion with the atomic weight shows that these rays arise from similar parts of the atom, and the evidence is very strong that they originate in the innermost ring of electrons. Barkla has shown, moreover, that the heavier elements give out a second characteristic type of radiation very much softer than the first, which again is connected in a simple way with the atomic weight of the element.

This radiation from elements of small atomic weights is exceedingly soft, so soft, indeed, that it has not yet been detected from any element with an atomic weight less than 90. This softer type of radiation probably originates in the second shell of electrons, counting from the inside of the atom. By the study of these radiations we thus get, in the case of the heavier elements, evidence of the existence of two groups of electrons. The radiation from the outer of these groups is so much softer than that from the inner, that if the increase in softness were to continue at the same rate, we should not expect, except perhaps for elements heavier than lead, to obtain radiations from a third ring which could be detected by the methods hitherto applied to Röntgen rays. The method thus breaks down as we approach the most interesting part of the atom.

I think, however, that we may hope before long to have at our disposal methods by which we can produce and investigate Röntgen rays of a much softer type than those hitherto used. Röntgen rays are usually generated by shooting rapidly moving electrons against a solid target; the greater the speed of the electrons the harder are the rays they produce. The softest characteristic radiation yet detected is that from aluminium; this type of radiation is produced by electrons moving at a speed corresponding to about 3,000 volts, and is so easily absorbed that it is difficult to work with in the open air. By working inside a very good vacuum, and using a special type of photographic plate, I have, however, been able to photograph radiations produced by electrons whose speed corresponded to only 20 volts, and by increasing the speed of the electrons, to get harder and harder radiations, until at last they were as hard as the kind hitherto studied. The softest radiations obtained in this way could not get through a film of collodion, though this was no thicker than a soap bubble; they are probably identical with those forms of ultra-violet light which are called, after their discoverer, Schumann rays; with these soft rays we may hope to fill up the interval between visible light and the hardest Röntgen rays. These soft Röntgen rays are, I am convinced, likely to prove of great service in investigating the question of the structure of the atom; they promise to enable us to determine the number of different groups or rings present in the atom, and to determine the number of electrons in each ring. Thus, for example, if we can measure the absorption of an element for the whole gamut of Röntgen rays, starting from those characteristic of a heavy element and going down to Schumann rays, then whenever the rays pass through a type corresponding to one given out by the element, there will be a sudden jump in the absorption; by counting the number of these jumps we could get the number of rings of electrons in the atom. Or if we measured the emission of Röntgen rays caused by the impact against the element of cathode rays of different velocities, there would be similar jumps every time the velocity of the cathode rays reached the value which could stimulate a Röntgen ray characteristic of the element.

We could determine the number of electrons in each ring by an extension of the method used to determine the total number of electrons in the atom. When

Röntgen rays harder than the hardest 'characteristic' radiation of an atom are scattered by the atom every electron does its full share of the work, so that the scattering measures the total number of electrons in the atom; if now we take Röntgen rays which, while softer than the hardest characteristic, are harder than any of the other types of radiation given out by the atom, they will not be scattered appreciably by the electrons in the inner ring, but they will be by all the other electrons; thus the scattering of these rays will give us the number of electrons not in the inner ring. We already know the total number of electrons in the atom; the difference of these numbers will be the number in the inner ring. Then if we measure the scattering of Röntgen rays softer than the next hardest characteristic, but harder than any of the others, we can determine the number of electrons outside the two inner rings; this, since we know the total number of electrons and the number in the first ring, will give us the number in the second ring. Thus, by measuring the scattering of softer and softer Röntgen rays, we can determine one after another the numbers of electrons in the rings.

The outer ring of all is the one which gives vibrations slow enough to come within the range of the visible spectrum; we might expect, therefore, if we measured the scattering of light well up in the ultra-violet, to be able to determine the number of electrons in the outer ring, which is in many connexions by far the most important of all. The scattering of light is very closely connected with the refractive index, so that if we know the refractive indices for light going well up in the ultra-violet we could also deduce the number of electrons in this ring. Drude some time ago, and more recently Erfle and Mr. and Mrs. Cuthbertson, have investigated the number of electrons in this ring on the assumption that it was the only one which influenced the refraction of ordinary light; the results they arrived at indicate that there is a close connexion between the number of these electrons and the chemical valency of the atom. In fact, they suggest that this number may be equal to the electro-positive valency of the element. It cannot, I think, be maintained that the experiments of Drude and others on the indices of refraction do more than suggest this identity. Many of the results differ considerably from those which would follow from it. We need not, however, I think, attach any very great importance to these discrepancies, as many assumptions were made in the course of the work for the sake of simplicity which may turn out not to have been well founded; it was assumed, for example, that there is only one period in the visible and ultra-violet light portion of the spectrum which enters into the expression for the refractive index, and this period was chosen not because it had been observed in the spectrum, but so as to fit in with the measurements of the refractive index. We must remember, too, that one or more of these mobile electrons in the outer ring may leave the atom when it enters into chemical combination, and that their arrangement is altered by the proximity of other atoms; as many of the substances used by Drude were compounds, the number of electrons in the ring may not have been the same as when the atom was in the free state.

The strongest evidence in favour of the close connexion between the number of electrons in the outer ring and the valency of the elements comes from the chemical properties of the elements, and especially the various types of chemical compounds they can form. Very many of these are simply explained by supposing that near the outside of the atom there are mobile electrons equal in number to the electro-positive valency of the element. The electro-positive valency is the valency when the element is acting as the electro-positive constituent of a compound, and, as Abegg pointed out, is in many cases connected with the electro-negative valency by the rule that the sum of the two valencies is equal to eight. An atom with n mobile electrons in the outer ring, or more generally one with an outer ring of electrons so constituted that when n of its electrons are fixed the others also lose their mobility, would in its relation to other atoms show the properties which the chemists describe by saying that the electro-positive valency of the atom is n.

Photographing atoms

I have alluded to several ways of investigating the structure of the atom ; they one and all involve great labour, and any one who has used them must often have felt what a boon it would have been if we had an eye which would enable us to have a good look at an atom and have done with it. Now I cannot say that any such eye has been invented, but Mr. C. T. R. Wilson has made some approach to it by a beautiful method by which we can see, not indeed the individual atom itself, but still the path of such an atom, and in some cases what is going on in the atom. The method is based on the principle that when charged atoms or electrons are produced in air sufficiently supersaturated with water vapour, the water condenses on them and nowhere else. Thus each atom or electron is surrounded by a little drop of water, and the regions where they are produced are mapped out by threads of little drops of water resembling seed pearls ; these can be photographed and studied at leisure. Now an electrified atom or electron travelling through a gas when it strikes against the atoms knocks some of the electrons out of them, and thus leaves behind it a trail of electrified wrecks. Mr. Wilson deposits drops of water on these wrecks, and thus the path of the electrified atom or electron is marked out by a trail of drops of water which can be seen and photographed. We can map out in this way the path of even one atom.

I think every worker at the Atomic Theory must have looked at these photographs with feeling akin to those of Adams and Leverrier when they first saw Neptune. Confident as one may be in the truth of a theory, there are few whose faith is so robust that they do not feel relieved when they see the conclusions to which they have been led by theory verified by experiment. Seeing is believing. Let me quote on this point a sentence by the great man who fills our thoughts to-day. Roger Bacon says, 'Argument may conclude a question but it cannot make us feel certain, except the truth be also found to be so by experience.'

To illustrate what this method can do, let me take two examples. It has been known ever since the discovery of Röntgen rays that when these rays pass through a gas they produce electrified atoms and electrons; if we take by Wilson's method a photograph of air when the Röntgen rays are passing through it, we find that the drops of water are not uniformly distributed over the photograph, but are strung together in fine lines giving the appearance of an untidy spider's web. This shows that when the atoms are struck by the Röntgen rays some of them give off electrons moving at a high speed; the paths of the electrons are indicated by the fine lines along which the water drops are arranged. Thus the electrons liberated by Röntgen rays start off at a speed which carries them a considerable distance through the air. Now let us take another case when electrified atoms and electrons are produced in a gas, the case when the gas is traversed by rapidly moving electrons or positively charged atoms; the photographs show that in this case the electrons liberated from the atoms for the most part start so slowly that they are unable to travel an appreciable distance from their origin. For if the electrons knocked out of the atoms by these moving particles had an appreciable fraction of the energy of the particles they would produce ions themselves, and a Wilson photograph would show branches shooting out from the stem formed by the drops due to the particle itself. Such branches are not altogether absent, but they are so sparsely scattered as to show that the great majority of the liberated electrons are not set free by direct impact between the electron and the moving particle, a view which is strongly supported by the very interesting result obtained by Lenard and Becker that the velocity with which the electron is shot out from the atom does not depend to an appreciable extent upon the speed of the particle which knocks it out. The laws of ionization by these moving particles are very different from those by Röntgen rays; it is not unlikely that the electrons ejected come from the outer layer of the atom in the first case and from an inner layer in the second.

The study of the effects of collisions of electrons or positively charged atoms with other atoms—on which Professor Townsend and his pupils have done such valuable work—raises very interesting and searching questions as to the dynamics of the collisions between these minute bodies. Indeed, as soon as we begin to study the properties of the atom questions such as these arise which go to the very root of dynamics and compel us to examine the fundamental conceptions on which that science is based. It is quite conceivable that the study of the atom may result in a considerable modification of the methods of regarding dynamical problems.

Though what we know about the atom is but a minute fraction of what there is to know, some very important conclusions about atoms have been established on what seems strong evidence in the course of the last few years. We know, for example, that there *are* such things as atoms, that the atoms of an element are all of one kind, that atoms of different elements contain a common constituent, the corpuscle or electron about which we know a good deal; we know, too, the number of electrons in an atom. We have strong evidence that the electrons in the atom are divided into groups, and that some properties of the atom, those which we associate with the innermost group, are connected in a very simple manner with the total number of electrons in the atom; that there are other properties, notably the chemical ones, which change in a rhythmical way with the atomic weight of the element, and which depend upon the electrons near the surface of the atom. We have evidence, too, that the atoms of the different elements are made up of simpler systems, and that considerable changes in mass have accompanied the aggregation of these systems. Lastly, we know that there are regions in the atom, probably the most interesting of all, about which we know little or nothing, whose investigation will provide intensely interesting work for many generations of physicists, who will most assuredly have no reason to be 'mournful that no new wonder may betide'. No fact discovered about the atom can be trivial, nor fail to accelerate the progress of physical science, for the greater part of natural philosophy is the outcome of the structure and mechanism of the atom.

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