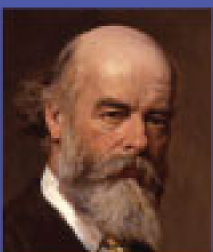
Atoms and Rays



Sir Oliver Lodge

ATOMS AND RAYS

Books by:

SIR OLIVER LODGE, F.R.S.

D.Sc. (Lon.); Hon. D.Sc. (Oxon.); Hon. Sc.D. (Cantab.); Hon. LL.D. (St. Andrews, Aberdeen, Glasgow, Edinburgh); Hon. D.Sc. (Liverpool, Manchester, Sheffield, Adelaide, Toronto); Hon. M.A. (Birmingham); Mem. Inst. Elec. Engineers; Hon. Mem. Lit. Phil. Soc. (Manch.); Corr. Mem. Amer. Phil. Soc. (Philadelphia); Corr. Mem. Accad. Sci. dell' Istituto (Bologne); Corr. Mem. Bataafsch, Genoots (Rotterdam); President of the Roentgen Society; Rumford Medallist of the Royal Society; Albert Medallist of the Royal Society of Arts, as Pioneer in Wireless Telegraphy; Ex-President of the Physical Society; Ex-President of the British Association; Ex-Professor of Physics in the University College of Liverpool; Ex-Principal of the University of Birmingham.

ATOMS AND RAYS
MAKING OF MAN
MAN AND THE UNIVERSE
RAYMOND: OR LIFE AND DEATH
THE SURVIVAL OF MAN
REASON AND BELIEF
CHRISTOPHER
THE WAR AND AFTER
MODERN PROBLEMS

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ATOMS AND RAYS

AN INTRODUCTION TO MODERN VIEWS
ON ATOMIC STRUCTURE & RADIATION

By SIR OLIVER LODGE, F.R.S.

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PREFACE

I WAS struck by a recent remark of that great mathematical and physical investigator, Sir J. J. Thomson, that though the present century had been extraordinarily prolific in discoveries in Natural Science, especially in the more physical branch thereof, there was very little popular knowledge or understanding of the matter. Nevertheless, there is a keen interest, even in the most abstruse things; as has been proved by the number of readers of books on the Einstein method of Relativity. And there is evidently a real desire to learn about anything which Physicists will take the trouble to expound with sufficient clarity to be generally intelligible. The present book is an effort in that direction.

To many of us it appears that we are certainly living in a Keplerian age: that is to say, in an age when all sorts of hypotheses are put forward, and are being compared with experiment and observation to see if they hold good, even if their *rationale* is not at the time understood, and although they may have to wait, for full explanation, for the Newtonian age which in process of time ought to follow. Some of us have even suggested that a Newtonian age is beginning now: not because any one man is of the magnitude of Newton, but because there are so many men well equipped with mathematical methods of investigation, and standing on the shoulders of the great men of the past. To some of these highly qualified thinkers it may be given to elucidate these at present obscure but vitally interesting facts and theories.

The general reader, and student desirous of information about modern progress in physics, will find the more technical chapters worthy of sustained attention; provided they are acquainted with the fundamental principles of mechanics and simple geometry. The algebraic knowledge assumed is insignificant, though every precise and formulated exact statement does certainly require time and concentrated energy for its complete assimilation.

The technical expert, already well acquainted with both facts and theories, may, it is hoped, feel stimulated by the introductory and more literary portions, and may sometimes be amused (or perhaps horrified) at a way of putting things, and may occasionally encounter a suggestive idea.

It is often thought by scientific men that once a statement has been properly formulated there is no need of repetition, no need for full discussion and exposition of it in all its bearings. Such discussion, to one still actively engaged in pioneering work, seems, and probably is, a waste of time. But it is only by treating a subject from many points of view, and by frequent repetition, that it gets any hold on the general mind. Effective exposition cannot be done crisply and compactly. Room and repetition are needed. Plentiful illustrations and analogies are a help. The fact that few take the trouble to provide anything like a literary exposition, must be partly the reason why appreciation of scientific discovery lags so far behind. Indeed in some branches of science the general public lags behind for more than a century. The fundamental truths of astronomy are now assimilated, and can be used for illustration and literary purposes; but how few other fundamental truths revealed by science can be so used, without a distracting feeling of effort and non-comprehension!

Men of letters know well that any great subject will bear multiple examination and discursive treatment; it must be threshed out and driven home repeatedly, if it is to effect an entrance and fructify. It is not enough for Shakespeare to have written, and Shelley and Keats and Browning: there must be books and essays and explanations and appreciations and criticisms innumerable. Whereas men of science, accustomed to speak only to their peers, are content if they can express something crisply and definitely and have done with it. Very admirable their work can be when properly done, and posterity appreciates and does justice to it; superlative merit is bound to be appreciated some day;

but there is room for another kind of treatment as well, and when a series of discoveries arouses enthusiasm it is only natural for someone with a teacher's instinct to try to interest all intelligent people, and not only the expert few, in the marvels that are being revealed.

Mr. Bertrand Russell, in his "ABC of the atom," has written an initial introduction of clearness and insight. The present book enters into more detail, but still aims at as much simplicity as the subject allows. Some of the chapters recently appeared as articles in "Beama." More advanced study might be well continued by help of a book called *The Structure of the Atom*, by Dr. E. N. da C. Andrade of the Artillery College, Woolwich. The student is asked to regard the present volume as introductory to more advanced treatises—say by Andrade, Kramers, Bohr, and Sommerfeld—and to read most of it rather as a recreation than otherwise. The processes of Nature should be enjoyable, even though the enjoyment is laboriously acquired. Their discovery is difficult enough, and is likely to be limited to a few; but their understanding requires little more effort than is often devoted to the solution of puzzles, and success is more highly rewarded. The more we learn about natural processes the more strongly they arouse the emotions of wonder, love, and praise.

OLIVER LODGE.

June 1924.

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ATOMS AND RAYS

CHAPTER I

THE GENERAL STRUCTURE OF THE UNIVERSE

In a book of mine called "Easy Mathematics," at the end of a chapter on Incommensurables and Discontinuity, occurs the following paragraph :

"On the surface of Nature at first we see discontinuity, objects detached and countable. Then we realise the air and other media, and so emphasise continuity and flowing quantities. Then we detect atoms and numerical properties, and discontinuity once more makes its appearance. Then we invent the ether, and are impressed with continuity again. But this is not likely to be the end; and what the ultimate end will be, or whether there is an ultimate end, are questions, once more, which are getting too hard."

The primary aspect of all Matter is continuous. Wood and plants generally, it is true, exhibit a fibrous or granular or cellular structure. But metals and liquids all appear to be continuous, so that there is no gap between one particle and the next, and so that the whole seems infinitely divisible. It was suspected by some of the ancients, however, and is now known to be true, that all Matter is composed of atoms, with interspaces between them, which in the case of solids must be filled with some kind of cement to account for their cohesion. A rough image is the way in which a house is built of bricks with intervening mortar.

Ingredients of Matter

A study of these atoms has revealed that the atoms of any one substance are all alike; but that there are a large number—nearly a hundred—of different substances which can combine into various compounds, and form by their regular and systematic aggregation the molecules of all the different materials that we encounter. And the science of

Chemistry largely consists in finding out and stating the laws of these atomic and molecular aggregations. Still, however, the science of Physics asserts that the molecules thus formed are not really in contact, but are held together by a substance which is responsible for their cohesion, and which is called the Ether.

A great deal more is known about the molecules of matter, and the atoms of which they are composed, than about the Ether, or cementing substance. It became known long ago—rather early in the last century, in fact—that the atoms were held together in the molecule by electrical forces, which accounted for what was called Chemical Affinity. And it began to be suspected, in later times, that the cohesion between molecules was due to some residual trace of this electrical attraction; so that cohesion was a subsidiary or residual kind of chemical affinity. Hence we might generalise and say that the atoms of matter, however constituted, were held and bound together under the action of electrical forces, according to laws which were to a considerable extent already ascertained and elaborated.

The Vehicle of Electricity

But to say that the force between the atoms was electrical is the same thing as saying that they are held together by the Ether. For " Ether " is only a name for the medium through or by means of which electrical force acts. It is, in fact, the vehicle of electricity. But not much was known about the nature of electricity itself.

Then, towards the end of the nineteenth century, it was discovered that electricity, too, was atomic, in the sense that it consisted of extremely minute particles, very much smaller than the atoms of matter, incomparably smaller; and that these corpuscles or particles of electricity were of two opposite kinds, equal numbers of each. One is the negative kind—which was first discovered—each corpuscle being called an electron; and the other the positive kind, about which less is known, each of which is called a proton. An atom of matter is really built up of equal numbers of these opposite particles; so that an atom can be analysed, and proved to consist of an aggregate of electrons and protons, grouped together according to certain well-defined and ascertainable laws. Hence the ultimate atom, or apparently indivisible particle, is now no longer the atom of matter, as had been thought, but is the atom of electricity; and of electricity all the atoms are made.

All that was previously discovered about the size of atoms, and the way they combine into molecules by electrical forces, and the way these molecules either hang together under cohesive forces to form the solids and liquids that we know, or fly about in a fairly free manner almost devoid of cohesion in what we call the gaseous state—all this remains true; though with some modifications, because the effective size of atoms, now that each is known to be a group or system, is perceived to be rather indefinite and dependent on circumstances. The rarer and cooler and purer the gas, the bigger may be the group that constitutes an atom; for alien and violent collisions may ionise it. But apart from that, and in addition to all this knowledge, the intimate constitution of the atoms themselves is now being revealed to us.

Sun and Planets in Miniature

Atoms are extremely, almost inconceivably, small; and yet they consist of parts which are millions of times smaller. And recently it has been found, and almost if not completely proved, that the atoms are constructed somewhat on the basis of a solar system; that is to say, that they have at the centre a massive nucleus consisting mainly of an aggregate of protons, with a definite number of electrons circulating round the nucleus, very much as the planets revolve round the sun. And furthermore, that the particles themselves are so small that their distances apart inside the atom are comparable with the distances of the planets from each other and from the sun, in the solar system, in proportion to the size of those bodies.

But obviously a solar system consists mainly of empty space; the part which is really occupied by matter being but a small fraction of the whole. It is manifestly extremely porous. So that any straight line drawn at random through it would be very unlikely to hit one of the planets, or even the central sun. Are we to suppose that an atom, too, consists mainly of empty space, and is as porous as a solar system? Yes, that is exactly the idea which the evidence conveys. And it must be regarded as an undoubted fact that an atom, though apparently so solid and impervious and full of material, is really a number of electrical specks, each of utterly imperceptible size, and occupying an insignificant fraction of the space included within the boundary of the atom: all the rest of which seems empty. If all the electrical particles which compose a human body could be violently compressed into absolute contact, the bulk would be reduced to a billionth part; and sixteen stone would then occupy only a fraction of a cubic millimetre, instead of twenty-two gallons.

The Welding Medium

The spaces between the particles are not really empty. They are full of the medium which holds the particles together, viz., the ether. And the same is true of the space inside the solar system. The planets are welded together into a family by means of Gravitation, which again is due to some unknown properties of the Ether of Space.

It is called the Ether of Space because it fills all space and every interspace. The space extending to the furthest star, the space between the sun and planets, the interstices between the atoms, and the interspaces in the interior of atoms—are all equally full of Ether. And the apparent discontinuity which the Atomic Theory suggests, the discontinuous nature first of matter and then of electricity, is supplemented or replaced by the absolute continuity of the connecting Ether.

It will probably turn out that there is some kind of structure even in Ether, but such structure has not yet been ascertained; and when it is ascertained, it is quite unlikely that it will be of a discontinuous character. Probably the Ether is absolutely continuous, though it may some day be found to have a texture which might be pictured provisionally as a number of vortices, like spinning whirls in a continuous ocean of water or air. Such spin may seem like a return to some of the ideas of Descartes. But it may be doubted if he realised how consistent vortices in a perfect fluid are with continuity.

Free Electrons at Work

Electrons are now known to be responsible for the conduction of electricity. In some substances they are fixed, crystallised as it were into each atom, without any freedom of locomotion. And such bodies are known as insulators. In other substances there are a certain number of electrons free; either absolutely free, or so loosely held that they are easily subject to locomotion, and are readily handed from one atom to another. Such bodies are known as conductors. And when a current of electricity passes along a wire, a stream of electrons may be thought of as penetrating the atomic interstices of the atoms of that wire. The stream is accompanied by a certain amount of jostling and obstruction and throwing into vibration of the atoms as they pass, which we observe under the name of heat; the filament of a lamp is purposely made so that this jostling of the atoms shall be excessive, and the wire become red-hot.

During conduction another remarkable phenomenon occurs. Whenever an electron moves, the space around it exhibits the phenomenon which we know as Magnetism. All magnetism is due to the locomotion of electric charges.

So long as they move steadily, electric force radiates from them, and magnetic force surrounds their path. But directly they are stopped or jostled, or whenever in any way their motion is interfered with, yet another phenomenon springs into being. The electric and magnetic forces then interact in such a way that a portion of the energy of motion of the electron is imparted to the Ether in which it is moving. And this portion of energy, thus imparted to the ether, cannot remain in position, but flies away with tremendous speed, which is called the Velocity of Light.

Transmission of Light

Why the Ether transmits energy at this precise and accurately known speed, is a secret at present best known to itself. It must depend somehow on its structure. All we know about it is that its structure must be what we call electromagnetic, and that the wave of light consists of simultaneous electric and magnetic oscillations, at right angles to each other, and advancing in a direction at right angles to both. Thus illustrating the well-known three dimensions of space.

Briefly, we may say, then, that when the motion of an electron changes—when it is started or stopped or accelerated or retarded—it radiates energy into the Ether, very much as a tuning-fork or a bell radiates sound into the air when it is struck. Supposing there were no air, if you struck a bell in a vacuum, there would be no sound. So also if there were no ether, and you struck or stopped a stream of electrons, there would be no light. Light is emitted because of the interaction between the atomic units of electricity and the ether in which they are immersed.

Radiation, Visible and Invisible

The term "light," strictly speaking, means that kind of etherial radiation which is able to affect the eye. But it is common knowledge that there are many other varieties of radiation besides those to which the eye is sensitive. It is not clearly known why the eye is sensitive to some kinds of etherial radiation, and not to other kinds. That, no doubt, can be ascertained; it is a question for physicists and physiologists in collaboration. But the eyes of animals and insects, as well as of man, all appear to be sensitive to a limited range of etherial radiation, which is therefore called *light*. Other kinds of radiation can affect a photographic plate; other kinds, again, can stimulate the chemical actions going on in the leaves of plants, and thereby supply the energy needed for vegetable growth. Another kind—a rather deeper bass as it were—supplies everything on earth with warmth, and by evaporating water contributes to most of the phenomena of weather. Other kinds, again, are emitted when individual electrons, travelling at a high speed in a vacuum, encounter the obstruction of a target; this kind of invisible radiation being called *X*-rays. And, at the opposite end of the scale, another kind of radiation is emitted by great aerials, and is known as the Hertzian waves employed in Wireless Telegraphy.

In speaking of these kinds of radiation as different, we are not speaking quite accurately. They differ only as treble notes differ from bass notes; they differ in rapidity of vibration or wave-length. They do not differ in any other essential particular. Through the whole range—from telegraphic waves, which may be a mile long, to *X*-rays, of which the wave-length is actually smaller than atoms, and only expressible in billionths of an inch—they all travel at precisely the same speed, the only speed at which the Ether is able to transmit energy. They are all of the same electromagnetic character; they are all subject to the same laws of interference, of reflection, refraction, and polarisation, which have long been studied in the department of physics known as optics. The fact that we possess in the eye a sensitive instrument for their detection, has enabled the human race to make experiments upon a certain range of Ether Waves from time immemorial, culminating in the brilliant and elaborate optical discoveries which aroused so much attention and were of typical scientific value in the early part of the nineteenth century.

Analysis of, and by means of, Light

It is chiefly by means of the kind of radiation emitted by the atoms of matter that their constitution has been made out. The light emitted can be analysed; the process is called spectrum analysis. And from a close and exact study of the position of lines in the photographed spectrum —whether that spectrum be formed by visible or invisible light—nearly all our knowledge of the intimate structure of the atom has been attained.

And this is what we find. That ninety-two kinds of atoms exist, and can be numbered exactly from one to ninety-two. The lightest and simplest, which is called Hydrogen, consists of one proton with one electron revolving round it. The heaviest and most massive at present known is called Uranium, and consists of 238 protons of which 92 are unneutralised, grouped together into a nucleus at the centre, and ninety-two planetary or satellite electrons revolving round it. Between these two extremes are the rest of the chemical elements. The one with two effectively charged protons at the centre and two revolving electrons, is called Helium. The one with three of each is called Lithium. Carbon has six of each, Nitrogen seven, Oxygen eight, and so on. Iron has twenty-six, Copper twenty-nine, Silver forty-seven, Gold seventy-nine, Radium eighty-eight.

Atoms that Explode

No wonder that Radium and the other elements at the top of this series are, by reason of their complex structure, rather unstable; so that their atoms occasionally explode, flinging away every now and then a superfluous electron and proton, thereby losing their original chemical character and becoming a different element. After Radium has flung away five such electric charges of each kind, it is indistinguishable from Lead. But it is very leisurely about it. Centuries may elapse between successive explosions of neighbouring radium atoms. And it is only because the atoms in any visible speck of matter are so extremely numerous that the activity of Radium is conspicuous.

Chemical "Keynotes"

The number and grouping of the satellite electrons determine the chemical properties of the different chemical elements. When they are grouped into a very compact pattern, so that they are complete in themselves, without excess or defect, they constitute the atoms of what are called the Inert Gases. They are gases because they have not even any residual chemical affinity: the atoms do not cohere together appreciably. And they have no other kind of chemical affinity. Argon was the first of these discovered; but subsequently quite a number—Helium, Neon, Krypton, etc. And these extremely stable groupings occur at regular intervals in the series of atoms; somewhat like the way in which C occurs at regular intervals on the keyboard of a piano, constituting octaves; the keynote of each octave in the chemical case being the atom of one or other of the inert gases.

On either side of an inert element will exist an element with either one more, or one fewer electric, charges; and these will be chemically active, and are called *monads* by chemists. They may be positive or negative in the sign of their activity, and they tend to combine furiously with each other. Chlorine is an example of one, Sodium of another, and their stable and satisfied compound, Common Salt, is familiar.

On either side of these monads there will be an element in which the stable pattern contains either two too many or two too few. These are known to chemists as *dyads ;* and these, too, are chemically active. Oxygen, for instance, on the one hand, and, say, Calcium on the other, combining to form Lime. Or instead of Calcium we might choose Magnesium as an example, for it is well known to burn—that is, to combine brilliantly with Oxygen.

And so on. The whole series can be dealt with in this way, and the chemical and other properties more or less explained.

A great deal more might be said about the discoveries which have been made concerning the structure of atoms, for not only have the electrons been counted, their orbits have been measured, their rapidity of motion ascertained, and the laws of their radiation made out. But to expound this would need a treatise, and some introduction or attempt at exposition is the object of this book. We may begin to summarise what we have learned already; for it is clear that we have made great strides towards understanding the constitution of the atoms of Matter, of which all the infinite material universe is composed.

The Building Stones of the Universe

First we have the absolutely continuous Ether. Then we detect specialised specks in it, the electrons and the protons. Then these combine or group themselves into the atoms of Matter. Then these form chemical molecules. And the molecules aggregate themselves into the visible bodies which appeal to our senses, and with which we are so familiar that we forget the wonder underlying it all.

The visible and tangible masses aggregate still further under gravitation into planets and suns. And the suns are so immense, their atomic jostlings are so intense, that they send out powerful and continuous radiation into the Ether which, falling upon the planets, keeps them warm and enables the processes of vegetation to go on.

Under this stimulus, therefore, the molecular aggregates no longer form only inorganic materials. They begin to group themselves into still more complex structures, and build themselves up into a material known as Protoplasm.

And then, mysteriously—at least, mysteriously to our present knowledge—a new phenomenon occurs. The protoplasm becomes, as it were, self-moving; no longer driven only by external forces, but exerting its own forces; crawling about, assimilating other materials and building them up into its own structure; not, like crystals, dependent on the kind of food supplied, but being able to utilise all manner of food, and yet building up its own well-defined and characteristic body.

This mysterious phenomenon, which makes its appearance when the organic molecules have attained sufficient complexity, and when they are stimulated by ether waves as received from the sun or other luminous body, is called "Life";—the lower kind vegetable life, and the higher kind animal life. And the animal life can not only assimilate food and grow; it can, when grown sufficiently, split into two, and then again into two, and thus increase in number. We see the beginning of what is called Reproduction, which develops again into many and various forms.

The Evolution of Mind

All this seems to lend itself to the process of Evolution. So that no longer Life is limited to the simple cells with which it began, but the cells themselves can aggregate together into large structures, just as the molecules did. And so, in the course of ages, at length appears the wonderful variety of animal life which we know of on this planet, culminating, let us say, in the oak, the eagle, and the horse.

Nor does the process of Evolution stop there. The higher stages of Life, for some reason which we can only dimly guess, begin to show purposiveness. They seek their food, escape from danger; they have become sensitive to all manner of influences. They have some foresight, they prepare nests for the young, they collect food in advance, they have some inkling of the future. They are more than mechanical; they exhibit the rudiments of what we know as Mind.

And then this Mind still further develops, giving the creatures which possess it an advantage over the rest of their kind. And in time it becomes Consciousness, clearness of apprehension, and a sense of free will, a power of choice, a knowledge of good and evil—and Man begins his strenuous career.

The Outcome of It All

So now at length the Power—whatever it may be—which has gone laboriously and patiently through all these early stages, and which has conducted the process of Evolution to its present state of development, begins to be rewarded by the existence of a creature which has the beginnings of sympathy and understanding, which is able to help and to guide evolution along further and unknown paths—a creature which is beginning to be conscious of its own destiny, and which is able to worship the Power which has brought it into existence, and to feel in the deep recesses of its nature something of a fellow-feeling and kinship and love both for the Creator and for the fellow-creatures which, like itself, are the outcome of all this planning and effort—the fruit of this marvellously beautiful universe.

CHAPTER II

ELECTRICAL CONSTITUTION OF MATTER

We have gradually learnt that electricity exists in two forms, the negative form which is called an electron, and the positive form which is called a proton. There is no other kind of electricity so far as we know.

The material universe seems to be built of these two elements. Both the electron and the proton are exceedingly small, very much smaller than an atom of matter. Both probably have weight; though one is much heavier than the other. The proton weighs as much as 1,830 electrons, but it is not appreciably any bigger, and some even think that it may be smaller than an electron. The fact is we do not know very much about it, except that it is the unit of positive electricity, just as an electron is the unit of negative electricity.

Fundamental Units

Whether the proton is an ultimate unit, or whether it can be resolved into a close-packed assemblage of simpler ingredients, such as would account for its remarkable weight or massiveness—remains for future discovery. It may have a complicated structure for all we know; but at present it seems to us one and indivisible. So does the electron.

Parenthetically, we may say that both are hypothetically supposed to be probably built up in an unknown way out of the ether of space; so that they need not be foreign bodies in the ether, but a specifically organised portion of it. But all this is at present hypothetical, and need not be emphasised, except that it is the only way in which it seems likely that they can move about freely without friction or resistance of any kind. Suffice it for present purposes to say that both electron and proton certainly exist; and almost as certainly that they constitute the apparently indivisible elements of which all matter is composed.

Size of Electric Units

They are, however, both closely related to the ether somehow; for they attract and repel each other. That is to say, there is a strong mutual force urging electrons and protons together, and at the same time keeping apart the units of the same kind; and this force, whether of attraction or repulsion, must necessarily be exerted through, and by means of, the intervening ether. Furthermore, we know that when either is in motion it is surrounded by a magnetic field, which magnetic field consists of some modification in the ether, and extends a considerable distance round the moving nucleus or kernel. These facts are commonly expressed by saying that a moving charge has two fields of force, one radiating from it in all directions, which is called its electric field; while the other, which surrounds its line of motion in rings—opening them out more and more, and crowding them closer together as the motion increases in speed—is called its magnetic field. This last it is which confers upon each unit its fundamental property of inertia—that is, its power of persisting in uniform motion until it is disturbed—checked or hastened or deflected—by some external force.

The size of these electric units is now known with fair accuracy. But is anything known about their shape? It is natural to think of them as spherical; there may be evidence for that shape; some reason can be given why they should be spherical. The spherical shape is characteristic of large masses of matter, such as suns and planets; and for good reason. A large enough body must be spherical; otherwise it is unstable. A great mass of matter of irregular shape, or even of regular shape like a cube or a cylinder or an elongated oval, could not remain in that condition. Its protruding portions would be pulled down and merged in the rest by gravitative attraction. The argument about electrons is different but not dissimilar, though less elementary. It belongs to a treatment of the ether.

Minute Measurements

But no force like gravitation is known to be able to act effectively on a small body. And accordingly the shape of a small body has to be ascertained by observation. It may be like a marble or a soap-bubble; but might it not be like a ring, or a sixpence, or a corkscrew? Or, again, could it be shaped like a feather, a seed, or a tadpole?

We assume that every proton is like every other; and that all electrons are alike too. But we do not know even that for certain. Meanwhile, it is natural and simple to think of them as little spheres, always bearing in mind that there is only questionable evidence for that assumption, and no evidence against it.

We know so much about these units, now, that it is well to remember from time to time the points about which we are still ignorant. We know approximately their bulk and their mass, or what is commonly called weight. But of their shape, structure, and constitution we are ignorant. We know that a proton weighs just about the same as one atom of hydrogen, but that it is in bulk a million million times smaller.

We know that an electron is comparable in size to a proton; but is 1,830 times lighter, or less massive. This 1,830 is an experimental number, and does not pretend to be quite accurate. It may turn out to be as small as 1,820 or as big as 1,850. But the best measurements lie between these two extremes; and 1,835 is a very reasonable value, according to our present information. This may seem unimportant; but I mention it as showing how precise our knowledge about these things is gradually becoming.

In the same spirit I can say that the diameter of an electron has been measured as $37\frac{1}{2}$ times the hundred million-millionth of a centimetre. And that the weight of an atom of hydrogen, with which we have above compared it, is 1·66 times the weight of a milligram divided by 1 followed by 21 o's. That is to say, that an atom of hydrogen weighs a million million million times less than a minute visible speck, such as a granule of lycopodium, which is about as small as can be weighed on a very delicate chemical balance.

A Miniature Solar System

That these minute corpuscles can build up gigantic bodies such as the earth, the planets, the sun, and the stars, is astonishing; like most other things in the universe when we dive down into them. But yet it seems an undoubted fact, for which the evidence is exceedingly strong—so strong as to be practically conclusive.

It has long been known and admitted that these great bodies are built up of atoms; and now we have learnt that the atoms are themselves built up of electrons and protons. And we have begun to learn what is the structure of an atom, that is to say, *how* it is built up out of its constituent elements—the opposite units of electric charge.

We are now, however, entering on a region where some debate is permissible, and some differences of enlightened opinion may exist. But the hypothesis which holds the field is that the atom is built up on the general pattern of a solar system. That is to say, that it consists of bodies arranged like the sun and planets, on a very minute scale.

We find a group of protons in the centre, half of them presumably welded together by a compact and interleaved assemblage of electrons, which are also able to hold on the other half of the protons as part of the compact group. This central group represents the sun.

Outside this nucleus, and at some distance from it, we find a regular series of electrons revolving round it, either singly or in rings, like the planets; or possibly in some cases, though less likely, like the ring of Saturn.

Furthermore, it has been found possible to count the outstanding or unneutralised protons and electrons in atoms of different kinds.

“*Ions*”

By “atoms of different kinds” I mean the chemical elements—iron, lead, zinc, carbon, oxygen, hydrogen, sulphur, gold, radium, and all the eighty-three other elements of which the world is composed. There seems no doubt about this counting; though it is a remarkable achievement. It is the result of work done by several living men, such as Rutherford and Barkla; and especially by young Moseley, who was killed by a Turkish bullet through his brain at Gallipoli.

The number of unneutralised protons at the centre, and the number of planetary or revolving electrons in any given atom in its normal state, must be the same. Many or few, there must be the same number of each; otherwise the atom would be electrically charged, and would not be in its normal condition. One electron too many would yield a negatively charged atom; two electrons too many would be doubly charged; and a few atoms might be even triply or quadruply charged. But such charging must be considered exceptional, and not likely to be permanent; for these additional electrons would be hanging on in the teeth of some repulsion, and would soon be likely to escape, unless this atom could find another with a deficiency, and combine with it into a molecule.

A deficiency of one or two electrons in an atom would mean that it was positively charged; and that, too, would be an unstable and exceptional condition. The electrical force exerted by such an atom would be very great, and it would soon be able to collect stray electrons and thereby restore the balance to equilibrium; or else it would combine with another, or several other, oppositely charged atoms, to form a neutral compound molecule. When the charge of an atom is unbalanced, or not neutralised, the atom is readily guided and propelled; and, as an easy traveller, it is then called an “ion.”

It is not to be supposed that the protons here spoken of as forming the central positive charge, together with the same number of planetary electrons surrounding it, are all the protons and electrons that exist in the atom; the nucleus may contain many more, and usually does contain about double that number.

Atomic Numbers

The planetary electrons are the most prominent, the most efficacious of all the atomic units, and, in fact, are those upon which the chemical properties of the element depend. The others, tight packed in the nucleus, contribute to the weight of the atom, but do not contribute to its chemical properties nor to its specific radiation. Part is like an inert mass of satisfied material upon which the other more active and demonstrative units are grafted. The compact central mass is electrically composed and highly charged; it may be responsible for some spontaneous and explosive radio-activity, and anyhow its charge controls the movements of the planetary electrons. The charged part of the nucleus contributes to electrical behaviour—which is the most conspicuous phenomenon in an atom, whether it be regarded from the physical or chemical side; the neutral part of the nucleus only contributes to weight and inertia and mechanical properties generally.

Consequently the inert part of the central mass is often ignored, and seemed to be of minor importance until some means was found for breaking it up. Attention was, and is, concentrated chiefly upon the outlying negative electrons and upon the corresponding number of protons which by their electrical attraction hold them together into a sort of solar system. These are what have been counted; and these are what are chiefly important to our present knowledge. But the others do not escape detection, and it is easy to count them too—in fact, quite easy, for they are responsible for the atomic weight, and are at once determined by the weight of the atom.

Given that an atom of hydrogen contains 1 proton, and weighs 1, then an atom with atomic weight 16 must contain 16 protons. But not all these are active; only 8 of them exhibit electrical forces and hold 8 electrons in orbital movement. The other 8 constitute the rest of the nucleus and represent its electrically neutral portion.

So also with an element of atomic weight, say 31; 16 of them are inert and 15 of them are electrically active. The active members are what determine its chemical and spectral behaviour, and their number is known as the atomic number of the element. Roughly, the active number is usually about half the total number, sometimes exactly half, though in all cases rather smaller than half when not exact.

Of this number there can be no fraction, and it proceeds regularly through the different elements from 1 to 92. Nearly all these 92 elements are known—there are only three or four gaps—and any day the few outstanding gaps may be filled by the active and enlightened investigators of the present day.

If we now ask how many electrically active protons, and how many electrically active electrons, go to make an atom of sodium, the answer is forthcoming. The number is 11 of each. If we ask the same question about chlorine, the number is 17 of each. If we ask it about carbon, the answer is that 6 of each kind of electric charge constitutes the effective part of the atom of carbon. If, however, we proceed to some of the heavier elements and ask the question about lead, the answer is the surprising number of 82 of each kind. If we inquire into the constitution of radium, we find 88 of each kind; 88 active protons along with 137 of the inert or satisfied variety exist at the centre, and 88 planetary electrons, either revolving or else grouped in some pattern, are attendant round the central nucleus or sun. The heaviest known element is uranium; and for that the number is 92. No element with a greater number than that is at present known. Possibly any greater number would be too unstable to exist for any length of time; so that it would be extremely rare. Even uranium is not quite stable; and if we were to watch an atom of uranium for a sufficient length of time—which would be a very tedious business, for we might have to wait a thousand years—we should see (that is, mentally "see," for, of course, an atom is hopelessly invisible) a group of four protons violently escaping; and we should see four electrons escaping, too, two packed up with the proton group and two thrown off separately; showing that of the four protons two came from the inert portion of the nucleus and two from the electrically active portion, so that the projectile retains a double, not a quadruple, electric charge.

The number remaining, of the active variety of each, would thereby be reduced to 90; which would mean that it was no longer uranium, but another element called uranium-*X*. This also would explode or fire off a particle in time, so that the number would then be reduced to 88, when the main or residual substance would be radium. Then it might go on with rather increased activity, though still only very occasionally as far as each atom was concerned, until the number got down to 82, with two well-marked intermediate stages, one of them called, by Madame Curie, polonium. The element with 82 active pairs would be fairly or perhaps quite stable, and would be indistinguishable from lead. If the number ever got down to 80, it would be mercury. And at 79 (though that is quite out of the true line of descent) it would be gold.

So much for the heavier, unstable end. But what about the lighter elements? Carbon, for instance, has only 6 pairs; oxygen has 8, nitrogen 7, lithium has only 3 of the central positive and revolving negative particles. Helium—which is that comparatively rare inert gas, found by Sir William Ramsay to be given off by certain minerals and by the hot springs at Bath and other places; given off also during the disintegration of radium, an element first discovered, spectroscopically, by Norman Lockyer in the sun, and hence called helium, or "helion," as we now see that it ought to be called—helium has only 2; whereas the first-known of the inert gases, the one discovered by Lord Rayleigh, viz., argon, has 18.

The helion atom has the atomic weight 4. So it must contain four protons in all, and, of course, also four electrons, though two of these seem more closely imbedded in the structure than the other two; but all of them are so tightly held that it has very little external field and, accordingly, is chemically inert—so inert that the atoms are unable, physically, to hold together by cohesion. Wherefore it exists as a gas consisting of isolated atoms. If they combined into molecules by residual electric attraction or affinity, their bond of union would be so slight that the smallest jostle or provocation would separate such atoms from each other; and accordingly it can only be liquefied at an exceedingly low temperature, very close to absolute zero. For at that low temperature the jostling practically ceases, and the atoms are so nearly quiescent that the bonds of their feeble residual affinity are not broken.

The fact that helium is emitted by certain radioactive minerals has been utilised to determine the age of the earth, or rather, in more detail, the age of the different rocks constituting the crust of the earth. The rate at which uranium, for instance, disintegrates is known. Its disintegration is accompanied by the emission of alpha rays, which immediately turn to helium. The helium so emitted is occluded by the rock: it does not actually escape, it is held mechanically, being in very small quantities: for to evolve a perceptible amount of helium, anything which might be called a small bubble of the gas, from any ordinary lump of the material, would take thousands of years. But by boiling and other methods, the occluded but chemically free helium can be extracted and its amount estimated. And in that way the present Lord Rayleigh has determined the age of many of the rocks, and therefore a lower limit to the age of the earth—which seems certainly not less than four hundred million years of age, and possibly a good deal more.

It may be objected that some of the helium would have escaped, and that it could not all be collected. That may be so; but in that case the estimate would be under rather than over the mark. The more helium there is, the older the rock. Any deficiency would lead to an under estimate of its age.

The atom of helium is very like one of those projectiles flung off by a radioactive substance and called an alpha-particle; but whereas an atom of helium is electrically neutral, an alpha-particle is by no means neutral. It has a double positive charge, it needs two electrons to satisfy it; but these it soon picks up, and then it becomes the completely satisfied and inert atom of helion. The $\overset{4}{+}$ and $\overset{2}{-}$ have become $\overset{4}{+}$ and $\overset{4}{-}$.

Is there any element that has only one constituent pair, one proton as the central nucleus and one revolving satellite; like an earth-moon system? Yes, the answer is definite and certain. The lightest known element is hydrogen; and hydrogen has only one of each. The hydrogen atom is constructed on the pattern of the earth and moon.

Unstable Elements

Thus there are exactly 92 elements, and no more. One cannot imagine an element lighter than hydrogen, unless it is possible to split a proton and an electron into fractions. It is easy to imagine an element heavier than uranium, or any number of them. Hence, in that sense, there may be more than 92; but not by interpolation, only by extension of the heavy end. And although such elements have been looked for—notably an inert gas with the atomic number 118, which might rather have been expected—none of them has as yet been discovered, and the evidence on the whole is against their probable or frequent existence. Though the possibility of building up still more complex, and probably still more unstable, elements, under special conditions of temperature and pressure, remains a subject for future discovery; and the most likely place for such an extension of the chemical series is in some of the stars.

The building up process we have not learnt how to accomplish; nor have we ever observed it going on. The tumbling down or disintegration process we have observed; it constitutes the phenomenon called radio-activity. But even that we are unable to control. It goes on spontaneously, or not at all. Nevertheless, it goes on with great violence. The atoms really do explode, as a cannon explodes, firing off a shot with great vehemence, at a speed of several thousand miles a second.

And the nature of this shot has been analysed. We might have expected it to be a proton. But, strangely enough, it is not. As stated above, it is a group of four protons welded together by two electrons, all apparently jammed together into a compact mass, without any satellites or revolving charges. The projectile really is a projectile, weighing four times as much as an atom of hydrogen. And, moreover, it is not in a permanently stable condition. It seems stable enough mechanically, but not electrically. It has four positive charges and only two negative. Consequently, it is electrically unbalanced. It has a double positive charge.

Effect of Atomic Projectiles

A projectile of that kind, moving at that tremendous speed, is quite a serious thing, and can do a lot of work before it is stopped. If it hits a phosphorescent substance, it emits a flash of light. If it strikes another atom it might do some damage.

But if an atom is like a solar system, we might well ask, What is there to strike? Will it not rather go through an atom? Certainly that is what is to be expected; and that is what happens. Atoms are exceedingly porous, just as porous as a solar system, so that a projectile going through them is quite unlikely to hit anything. But every now and then it may; and sooner or later it must, on the doctrine of chances. It may go through ten thousand atoms without hitting anything. But if ten thousand projectiles were loosed through the solar system, at such speed that gravitation had no appreciable effect, one of them at least might hit the sun, and then something would happen.

Disintegration

Sir Ernest Rutherford has tried the experiment with nitrogen. He has got one of the radio-active materials, an offspring of radium, to fire its projectiles through nitrogen gas. Thousands of them hit nothing, or only encounter one of the electrons, which they may be able to sweep up and carry away without much disturbance, as an electron is such a light thing. But occasionally they may hit the nucleus. And the nucleus of nitrogen is fourteen times as heavy as hydrogen, while the projectile is four times as heavy. Hence the encounter is no trifle. The experiment is like firing a crowd of suns, each a quarter the weight of our sun, through the solar system. Many go through free and go on, some might sweep up and carry away one or other of the seven planets. (Seven in the case of nitrogen.) But one, by chance, encounters the "sun" itself. There is a smash, and the sun breaks up.

The atom of nitrogen is disintegrated, not by spontaneous radio-activity and by its own energy, but as by the explosion of a shell or the impact of a violent projectile. And what happens to it? Is it dispersed into its constituent protons, or do some of them hang together still? The answer can only be given by experiment. And the answer found by Rutherford is something like this: That most of the protons hang together in groups of four, constituting three atoms of helion, while two odd ones are flung out with great speed—even greater than that of the projectile which drove them—so that we get violently ejected atoms of hydrogen.

Structure of Nitrogen Atom

The above looks as if the atom of nitrogen were really composed of three helion and two hydrogen atoms—as if it were a compound of those primary elements—and that it was disintegrated or broken up into its constituents by the impact of an alpha-particle.

But it is surely unlikely that it is really a compound of that kind; independent helion atoms are not likely thus to hang together. The atom of nitrogen may have a structure of its own, which is not really compounded of the elements into which it may nevertheless be broken up, any more than we need say that water actually consists of hydrogen and oxygen, though it turns into those gases, and nothing else, when decomposed.

It is, perhaps, a question of expression. Aston has asked a corresponding and relevant question by the words, Does a pistol contain smoke? Some might say, Yes, because smoke comes out of it when fired, so it must have somehow been inside; others might say, No, the smoke is generated by the explosion, and was not pre-existent. Neither statement need be false. But which is the more convenient?

Suffice it therefore to say that an atom of nitrogen can demonstrably be broken up into helion and hydrogen, but that what its constitution may be like before it is broken up is a question to which an answer can only be guessed, for it is as yet by no means surely ascertained.

A Great Experiment

What is certain in this experiment is that two atoms of hydrogen are driven out. What is uncertain is what becomes of the rest of the nucleus. If it still clung all together it would be an atom of carbon; which would be unlikely. Most likely it breaks up into three atoms of helion. But other groupings can be suggested, and possibly the particular grouping may depend on circumstances. The evidence goes to show that hydrogen is certainly projected, and helion probably. But it is a great experiment! For the disintegration of a chemical element had never previously been performed by artificial means. I do not say that nitrogen is the only one that has been dealt with, but I take it as the type. This breaking up of an atomic nucleus is one of the latest things discovered.

CHAPTER III

MORE ABOUT ELECTRONS, ETHER, MATTER, AND ENERGY

The Electron

(1) The first outcome of the brilliant work that has been done in the last quarter-century, both in the laboratory and the study, has been the discovery of the discontinuous nature of Electricity; that is to say, that an electric charge is not a continuous thing, as had been thought, but is due to an aggregate of separate units, called electrons. An excess of electrons confers on a body a negative charge, the phenomena of which have been familiar since the time of Benjamin Franklin, and before that. A defect in the normal number of these particles or electrons constitutes what has long been known as a positive charge.

At first sight, these terms seem inapplicable, or inverted—which would not be surprising, seeing that the terms were applied long before electrical phenomena were even partially understood. But it turns out that there may be justification even for this inversion: for Franklin's curious guess that one of the two opposite signs is associated with what may be called "electricity," while the other is more associated with what has been called "matter," is tending to be surprisingly justified. And it may be held, not unreasonably, that there is something in the material or positive portion more substantial, and at any rate more massive, than can be attributed to the comparatively subordinate or attendant kind of entity, the isolated negative charge or electron proper.

The discovery of the electron does not render nugatory the long-continued study of the subject throughout the last century: it only supplements that study. And even though we now regard an electric current as due to a torrent or stream of electrons, that in no way militates against the truth of the electromagnetic laws and phenomena existing in the space surrounding an electric current. All the lines of force are in that space; most of the phenomena occur there; and all the laws of electromagnetism hold unchanged. But the roots of the lines of force, instead of being located indefinitely on the conductor, are now each of them anchored to an electron—a particle which has a separate identity and individuality of its own, a thing which can be weighed and measured, its speed determined, and its activities brought under control.

What is still hidden from us is its intimate nature. We do not know what the electron itself is, nor how it has attained its remarkable properties. We surmise that it must be a knot, or a strain, or a singularity of some kind, in the Ether of Space, through which it moves quite freely, without resistance, as if it were perfectly at home, and not of the nature of a foreign body; not at all like a grain of sand moving through a liquid.

We know now that all electric charges are due to electrons; that all electric currents are electrons in motion; that all magnetism or magnetic lines of force surround moving electrons, being more and more expanded and conspicuous as the motion becomes more rapid. And we know also that radiation, or what is popularly termed light, is due at its source to changes in the velocity of electrons; and that the highest kind of radiation, or *X*-rays, spring into existence when a quickly moving electron is suddenly stopped, or has its motion suddenly reversed. The phenomena of Electricity, Magnetism, and Light, are thus welded together into a comprehensive whole, after the manner begun by that great genius Clerk-Maxwell in the year 1865, and extended and made more concrete ever since by all the relevant discoveries that have been made.

The Atom

(2) The second great outcome of the work that has even more recently been done, is the establishment of the Electrical Theory of Matter, whereby it is now known that

all the familiar objects which now appeal to our senses are really composed of a multitude of electrical charges, and of nothing else; or at least if there is anything else, the burden of proof rests on the asserter. The electrons themselves, however, though called upon to explain the greater part of the phenomena known as electric charge, electric current, magnetism, and light, are incompetent to explain "matter." That is dependent mainly on the identity of the positive charge, which long remained an unknown puzzle, but which is now beginning to give up its secret.

The atom of matter is now almost universally regarded as a central positively charged nucleus, surrounded by a definite assemblage, not a crowd but an orderly array, of electrons; the number of which differs in the different atoms, according to the qualities of the nucleus which they surround. Some think that the surrounding group of electrons are stationary, and, as it were, crystallised into position, under the action of some, at present unknown, forces. This may be called the chemical view. It is upheld, and ingeniously developed, by Professors Langmuir and Lewis in America. Others regard them as subject to the laws of dynamics, that is to say, to the kind of laws which were applied by Newton in Astronomy; and therefore necessarily revolving round their attracting centre in regular orbits, as the planets revolve round the sun. Physicists nearly all take this kinetic view of the constitution of the atom; and Professor Bohr has elaborated this theory with remarkable skill.

Which is right, for our immediate purpose, does not matter. What all agree is that there is a nucleus, with a known and definite positive charge, and that the electrons surrounding it are sufficiently numerous exactly to neutralise that positive charge, at any reasonable distance from the normal atom. A chemically active atom will have one or more electrons too many, or too few. And this excess or defect of charge confers upon the atom strong chemical properties, and converts it into a rapid *traveller* or "ion." Combination between these ions constitutes the backbone of the phenomena of Chemistry; a science which has long studied all the possible groupings of atoms into molecules with astonishing skill and success.

The Nucleus, and the Proton

The main feature of interest now is the constitution of the nucleus, which has been investigated chiefly by Sir Ernest Rutherford. The central feature of the nucleus, the unit of which it is built up, is the proton, or smallest unit of positive charge. Alone it constitutes the nucleus of the hydrogen atom, and may be regarded as the fundamental unit of matter. All other nuclei can be built up of a definite number of protons and electrons, the number of protons being in excess, so as to leave a compact group with an unbalanced positive charge. The total number of protons in the nucleus gives us what is called "the atomic weight." And the number of unbalanced protons, those which have to regulate the crowd of attendant electrons, gives us "the atomic number." For chemical purposes, the atomic number is the more important, though the atomic weight of different elements has been determined for more than a century, more or less ever since the time of Dalton.

The intrusion of arithmetic into the structure of the atom of matter is very curious—the fact that it is built up of constituents that can be counted, and of which no fractions appear possible, is most important. The atomic number is a whole number, and ranges over the different chemical elements from 1 to 92. But the strange thing is that the atomic weight is also a whole number, though not obviously so. There are no real fractions in the atom; though one of the familiar elements may consist of an admixture of slightly different though chemically similar elements, differing only in weight, and so giving a fractional atomic weight on the average. Our certainty on this point is due to the investigations of Dr. Aston, carrying out a method originally devised by Sir J. J. Thomson.

Matter and Energy

So much for the main features of atomic constitution; but we must proceed to show that this view of matter has very remarkable consequences. Whatever an electric charge is, or is not, it is certainly a focus of energy. And if we could imagine an Ether vortex, containing the known mass of the electron, and circulating with the velocity of light, its energy would be equal to that of the electric field in the space surrounding the electron. This coincidence, if it be a coincidence, can hardly fail to have some meaning. And there are those who are beginning to think that the whole material universe is built up of Ether in various states of self-contained or intrinsic motion; by which adjectives it is intended to discriminate between rotatory motion, like that of a top or a whirlpool, and ordinary locomotion, or shifting from place to place. Locomotion is not to be attributed to the Ether, which is the most stationary thing we know, perhaps the only stationary thing that exists, but it may be full of what is sometimes called "stationary motion," a paradoxical term appropriate to the condition of a sleeping top.

Those who hold this view of the universe are strengthened in their position by the remarkable expressions developed by the genius of Einstein for energy in general. It is well known that all the ordinary energy we are acquainted with, such as the motion of railway trains, cricket balls, and such like, is merely relative—relative to the earth, or to some other piece of matter. There is nothing absolute about it. But Einstein gives an expression for what I am inclined to call absolute energy, in which the only relevant velocity is the velocity of light. And all the phenomena we observe in nature, at any rate in inorganic nature—omitting the phenomena of Life and Mind for the present, as lying outside our physical ken—may be regarded as due to, and as demonstrating, slight modifications of the portion affected by this great etherial velocity, in a form which enables it to appeal to our animal-derived senses. For the spinning motion itself is impalpable and beyond the ken of our instruments, until it partially exhibits itself as transmitted waves in the form of radiation.

The Ether

All the light that we experience can be resolved into vibrations or tremors in the Ether. That is how we first knew about the Ether. But all electric and magnetic phenomena, and therefore all chemical activity, are likewise known to be modes of manifestation of the Ether of Space, the complete manner and meaning of which have still to be worked out.

So the question arises, What is Matter? Is that too a manifestation of some peculiar properties in the Ether? We know now that matter is built up of protons and electrons. But when we come to analyse these into their fundamentals, we find more than a hint that they are but special modifications in the all-pervading ether, and are essentially resolvable into etherial energy of a specific kind. Hence we are beginning to think that matter itself is a form of energy.

Energy is the chief thing in the physical universe that directly appeals to us. We apprehend it under a great variety of forms. And it is becoming probable that what we call matter is one of those forms. Most of the forms of energy that we know are convertible one into another. The energy of motion turns into heat; so does the energy of electric currents, unless it is converted into the energy of chemical separation or electric charge. Conversion from one form to another, without loss, is the sign-manual of energy. And the proof that matter is a form of energy will not be clinched until it can be demonstrated that matter too is convertible into other forms of energy.

Interlocking of Matter and Energy

Such a process has not yet been performed in our laboratories, though it is believed to be occurring in the giant stars, the interior of which is at an altogether exceptional temperature and pressure, and constitutes a laboratory where results can be obtained beyond the scope of our present manipulation. In the *light* from those stars, we see some small residual outcome of this production of energy at the expense of matter. In their motions, we probably see the same thing. That which we ordinarily recognise as the locomotive energy of bodies, seems now to be the mere overflow or surplus of the violent constitutional energy within—energy which at present seems inaccessible to us, which we have no means of getting at, but which is possessed in enormous amount by the very constitution of the atoms of matter. Fortunately, a few of those atoms have given us the hint. They have spontaneously emitted a small fraction of their energy. We call it radioactivity; and it is only the heavy atoms, such as radium, and other substances at that end of the series, which still retain the property of spontaneous disintegration. The other more familiar atoms seem to have lost that power, and settled down into apparent stability and quiescence They show no obvious sign of possessing any, but to the eye of science it is there; and means have even been sought, rather than as yet suggested, for getting at it.

New Sources of Energy

The combination of atoms into molecules, and the interaction of molecules generally, has long been known to give rise to various forms of energy. Witness ordinary combustion, and the power of explosives. But if simple atoms, like those of hydrogen, could be packed together so as to form the more complex atoms of higher elements, such a process would liberate vast stores of energy, much greater than could be obtained from ordinary kinds of chemical combination. It is highly unlikely that this will go on spontaneously or uncontrollably or dangerously, under such conditions as we are familiar with on the earth. They may be violent enough under the conditions in the interior of stars, including perhaps our sun. But here, on the earth, it is likely that they would be tractable, guided, and controlled, by human ingenuity; just as fire can be guided and controlled, and need not be allowed to run rampant and do damage, except by reason of bad or malevolent arrangements; and even then only on a very small scale. Let us hope that when this power is attained by man, humanity will have become sufficiently sane and civilised to use it only for beneficent purposes.

CHAPTER IV

POSSIBILITY OF HARNESSING THE ATOM

The atomic weight of Hydrogen is not exactly 1, but by careful measurement is found to be 1·0077. Who could imagine that in this slight discrepancy—which indeed needs some explanation to make intelligible—an immense store of possible Energy is indicated, which some day may become accessible for good or ill to the human race?

Let us first expound the meaning of the statement. For the bare statement that the atomic weight of Hydrogen is 1, or nearly 1, conveys nothing whatever unless we know the unit in which it is measured, that is to say, unless we have something to compare it with. For, of course, all measurements are relative to something.

Well, it so happens that rather more than a century ago, viz., in the year 1813 (when the atomic theory of Dalton was ten years old), Prout made the observation that the atomic weights of all the elements, as then ascertained, on the basis of taking Hydrogen as 1, were too nearly whole numbers to be the result of chance; and accordingly made the suggestion that the outstanding discrepancies might be otherwise accounted for. He surmised that they really were whole numbers, and not fractions, so that possibly all the elements were multiples or aggregates of Hydrogen.

The hypothesis, after exciting some interest, went into disrepute for a long time; though admittedly a great number of the atomic weights, as determined by chemists, were very close to whole numbers. But there were a few exceptions that could not be overcome, of which the most notable was Chlorine, whose atomic weight was unmistakably $35\frac{1}{2}$; and no contrivance could make it 35 or 36. If it had been like Potassium 39·1, or like Iodine 126·9, a little contrivance, or assumption of error in experiment, would have allowed these to be interpreted as whole numbers. And there were many of the atomic weights in this reasonable position. But there were some that were recalcitrant; not only Chlorine, but say Silicon, which was 28·3, and Magnesium, which was 24·3. And the outstanding fractions were more than could easily be got rid of. Hence, though there was something admittedly puzzling about the near approximation of so many to whole numbers, the hypothesis of Prout that all the elements could be built up of Hydrogen, with the atomic weight 1, fell into discredit.

Nevertheless, it was not altogether killed. For Sir William Crookes in 1886, at a meeting of the British Association in Birmingham, made a suggestion that perhaps the elements were not such simple and well-defined things, and the atomic weights not quite so numerically definite, as had been thought: that what we call Magnesium, for instance, might possibly not be a single substance but a sort of average—a certain proportion with atomic weight 24, mixed with another smaller proportion of atomic weight, say 25 or 26—the proportion so adjusted that the combined weight should come out 24·3, or thereabouts. In other words, that the experimentally determined atomic weights were averages rather than exact figures; though admittedly chemical skill allowed these averages to be determined with surprising accuracy. Indeed, some great chemists made these determinations their life work.

It is worth while to quote Crookes's words in this connection, published as they were so long before any verification was possible. This is what he said:—

> I conceive, therefore, that when we say the atomic weight of, for instance, Calcium is 40, we really express the fact that, while the majority of calcium atoms have an actual atomic weight of 40, there are not a few which are represented by 39 or 41, a less number by 38 or 42, and so on.

This idea, when thrown out, was only a hypothesis, a guess, a suggestion. Or, as Crookes himself called it, "an audacious speculation." But, like many of Sir William Crookes's ideas, it was based upon an instinct not to be despised, and was worthy of such testing as might be possible. At the time, no such method was available.

The discrimination or separation of the constituents of elements, on the supposition that there might be such constituents, could not be effected by purely chemical means. For presumably every constituent which grouped itself about the average value, though it might differ slightly in atomic weight, must have identical chemical properties. Otherwise they would have been separated long ago, and not called by one and the same name.

The possibility of the existence of such elements—of which the atoms differ in weight but in no other particular, having all their chemical properties exactly the same, and giving the same identical spectrum—suggested itself anew to Professor Soddy, in connection with his work on radio-activity. And he called them *isotopes;* meaning that they occupied one and the same place in the chemical series of Mendeléef. This well-based suggestion of Soddy's may be dated as promulgated in 1910. Soon afterwards, in 1912 and 1913, a remarkable method of analysis by physical means in a vacuum tube was invented by Sir J. J. Thomson—a method known as positive-ray analysis. And this was forthwith applied in an improved form by that indefatigable worker, F. W. Aston (who went from Birmingham to Trinity College, Cambridge) with remarkable and striking success, confirming to the hilt both Crookes's speculations and Soddy's half-ascertained results. The simultaneous communication of these vital discoveries, with the assured conclusion that atomic weights were really whole numbers and that all the fractional part was due to a mixture of different whole-number *isotopic* ingredients, was made to the British Association at Birmingham in 1913; one to the Chemical and one to the Physical Section, by Soddy and by Aston respectively, twenty-seven years after Crookes had thrown out his speculation in the same city.

Aston was able to show that Chlorine, with its atomic weight $35\frac{1}{2}$, or with greater accuracy 35·46, was really a mixture, in unequal proportion, of two elements, exactly like Chlorine and occupying the same place in the periodic table, so that they could be appropriately called *isotopes;* but of which the atomic weight of one was 35 and that of the other 37, the proportions being about three of the lighter to one of the heavier elements. And again that Silicon, with its atomic weight 28·3, was an average or admixture of two real elements, 28 and 29.

Not all the so-called elements are mixtures. Carbon, for instance, is exactly 12, Nitrogen exactly 14. Magnesium is a mixture of three, with atomic weights 24, 25, and 26. And Argon, though most of its atomic weight is 40, seems to have a slight admixture of a similar substance weighing only 36.

But now, on what scale are these numbers specified? What is the unit? Well, the unit is such that shall make some one of these elements of simple constitution exactly a whole number; and the scale chosen is that Oxygen shall be 16. Then all the others fall into place. On that scale Carbon is exactly 12 and Helium exactly 4. But, strange to say, Hydrogen is not exactly 1: and no amount of contrivance can make it 1. It is 1·0077, by the most careful weighing—weighing as carefully conducted as that by which the late Lord Rayleigh discovered Argon.

How then can we say that Prout's ancient hypothesis is substantiated, or that there is any probability in the idea that the elements can be built up of hydrogen atoms? All we can say, so far, is that they appear to be built up of some units which can be counted, and which only occur as integers, not as fractions. Whether this something is, or is not, a hydrogen atom remains for further exposition.

This exposition may be approached in two directions, both strongly confirmatory; one experimental, the other theoretical. Perhaps we had better take the experimental one first, as it is the simpler of the two.

The atoms are known to consist of massive nuclei surrounded by much lighter electrons. Practically all the atomic weight is in the nucleus. Even in Hydrogen, which has the lightest nucleus, that nucleus is about 1850 times as massive as an electron. Whereas in a really heavy atom like Uranium it is 238 times heavier still. Hence, when we speak of the atomic weight, we mean the weight of the nucleus. And if the atom is to be built of Hydrogen, it must be that the nucleus is so composed. No one imagines that electrons are responsible for the weight of Hydrogen. Hydrogen is a positive nucleus with one outlying electron. And if the nuclei are composed of Hydrogen, it must be of hydrogen nuclei tightly packed together, so as to form the compound nucleus of heavier atoms.

It was known that these nuclei were small compact things, and that they were positively charged; but very little else was known about them until Sir Ernest Rutherford found a means of knocking them to pieces, and thus seeing what they were built of. The only way to attack them is by their peers. They could not be shattered, or got at in any way, by any such trivialities as high temperature, extreme cold, enormous pressures, chemical explosions, or anything of that kind. They were far beyond the reach of these trifling perturbations. But the projectiles fired off by Radium, at a speed of several thousand miles a second, were not so insignificant. And Rutherford arranged to bombard the nucleus of any desired atom by means of these projectiles. The nuclei were targets excessively difficult to hit, because they were so ultra-minute; and thousands of shots might go by them without achieving anything. But then, hundreds of thousands of shots were available, any number in fact; so that sooner or later there was bound to be a hit. And then something happened. Briefly, the nucleus broke up, and Hydrogen flew out of it. The evidence for this must be read in Rutherford's papers. The evidence is given for the propulsion of a quick flying hydrogen-atom, driven out of the nucleus by the bombardment.

Well, this was pretty direct evidence that the nucleus contained Hydrogen, or at least contained it in the same sense that water contains it. For Hydrogen can be driven out of water by an electric current: in that case, it is true, a very perceptible or possibly a large amount, whereas in Rutherford's experiments only one or two atoms are ejected. But we are accustomed to deal with atoms nowadays, and to recognise them individually. And the evidence is sound. It does not prove that the atom is built of Hydrogen and nothing else; but it proves that Hydrogen is one ingredient. What else was knocked out of it? Atoms of Helium? Yes, probably. But we knew that atoms of Helium were there before, at any rate, in many atoms, for they are spontaneously ejected during radioactivity. Hence, it looks as if everything was built of Hydrogen and Helium.

So, now, we have to consider what Helium is built of. Its atomic weight is 4 exactly, a whole number. Hence if Hydrogen were 1, we should have little doubt that it was built of four atoms of Hydrogen, very closely compacted together. But the atom of Hydrogen seems too heavy for that. It is not 1. It is 1·0077. How can we say then that four atoms of Hydrogen can by any possibility build an atom of Helium, with atomic weight 4? It ought to be 4·03; but it is not. Why not?

Well, here comes the theoretical part of the exposition, the part which I said was rather hard. We have now to enter upon the electrical theory of Matter. We know now that Matter is electrically constituted, and that what we call its inertia is really due to the magnetic field of moving electric charges—that inertia is electrical, or in other words an etherial property; we know that inertia or massiveness is not due to something *in* the ultimate unit of Matter, but to something surrounding it. The observed inertia of an electric charge may be ascribed to the Ether which it carries with it. But that is too vague and indefinite to be useful. It is preferable to say that inertia is explicable in terms of electro-magnetism : that every electric charge has a certain mass associated with it, and that in an aggregate of electric charges their masses are added together.

But here comes the delicate point. When electric charges are squeezed close together, they interfere with each other to some extent. The positive and the negative tend to neutralise each other. If they could be jammed into complete coincidence, it must be supposed that they would obliterate each other. That, as far as we know, is not possible. But they can approach very near each other. And, by this close approach, their effect is neutralised as regards distant observation, or at least almost neutralised; and their inertia is diminished. Two opposite charges at a reasonable distance apart will have double the inertia of one. But if you pack them too tightly together, the combined inertia will be less than double. Some of their mass will apparently have disappeared—gone out of existence.

Now we said that a helium nucleus, if it consisted of four atoms of Hydrogen, must have those four atoms packed very tightly together. There are four positive charges, held together with two negative charges; and the tight packing would result in a diminished mass, a loss of weight; the aggregate will not weigh four times the original unit, but something less. In other words, not four times 1·0077, but only four times 1. That is the kind of thing to be expected. That would account for the disappearance of the ·0077; for this decimal part belongs to Hydrogen isolated, not to the Hydrogen used as the building brick for other atoms. Helium, and all the other atoms, *may* be composed of Hydrogen, but of tightly packed Hydrogen. And accordingly, Hydrogen in combination is 1, while Hydrogen free is 1·0077. Something has disappeared in the packing.

But this looks as if Matter could go out of existence. How is it possible for the seven or eight parts in 10,000 parts of Hydrogen to disappear and leave not a trace behind? What about the doctrine of the indestructibility of Matter?

But we have never yet said that it left no trace behind. That is just what we have to consider. If Matter ever disappears, what are we to expect instead?

Here comes in the theory of Relativity, which states that in some sort Matter and Energy are interchangeable. If Energy ever disappears, we must expect to find generation of Matter: and if Matter ever disappears, we must expect to find evolution of Energy. Now, so far as we have gone at present, neither of these things has been done in the laboratory. No one has seen Matter converted into Energy, or *vice versa*. It would be an important day when it was done. But I expect that some day it will be done.

We might stop to ask for a minute how this can possibly be understood. What physical notion can we form of the conversion, or inter-relation, between Matter and Energy? In my view, only through the intervention of the Ether. The Ether has associated with it an absolute, well-known, though great, velocity—the velocity with which it can transmit waves; but which is also, in my belief, a constitutional velocity, technically called the velocity of light. Parts of the Ether which are circulating in vortex or rotational motion with this velocity are what we must look to for the explanation of the fundamental part of atoms of Matter. A whirling structure in a fluid would simulate solid properties, and would have an identity of its own; as Helmholtz and Lord Kelvin long ago showed. If then this individual circulation is interfered with, or opened out, its Energy becomes conspicuous. It ceases to be a matter unit and becomes an energy unit.

But the Energy of anything moving or circulating with the velocity of light is something portentous. For the energy involves the square of that velocity. And even a grain of dust moving at that speed could do work equal to thousands of foot-tons. The energy of 1/10th of a milligramme, the smallest visible or weighable speck, moving with the speed of light, equals that of a load of 600 tons falling a mile!

If then the whole of any perceptible portion of Matter disappeared, the Energy resulting would be prodigious. When Hydrogen is packed into Helium, the *whole* runs not the slightest risk of disappearing. But 7 or 8 parts in every 10,000 do disappear. The 1·0077 becomes 1. And though the disappearing fraction is small, yet the total of which it is a fraction is so gigantic that the result would put all our other sources of Energy to shame.

But we have not learnt how to pack Hydrogen into Helium or into any other of the heavier atoms, have we? No, not yet. And yet it would appear that it must have been done, some time and somewhere; perhaps in the interior of stars, certainly in ways at present unknown. And, if so, some of the Energy associated with Matter may be accounted for. This is believed to be why the stars are hot. I suggest that some small fraction of this outburst of Energy may account for their rapid motions. All the heavenly bodies are moving, and all the big ones are hot; roughly speaking. The total Energy is beyond anything that can be accounted for by any of the forces known to us; it cannot be accounted for by any except what has now been suggested—the liberation of a fraction of Energy by the close packing of a simple element so as to form more complex ones. Or conceivably, in some cases, by the disappearance or destruction of Matter (cf. p. 200).

Ordinary combustion is due to the packing together of atoms into molecules, a very loose kind of coupling, giving a very small amount of Energy. The packing of protons into atoms or atomic nuclei is a much closer and more violent kind of phenomenon. And the undoing of atoms or electrons into non-circulating Ether is the most violent of all.

The Sun is hot enough, 6,000° Centigrade or 10,000° Fahrenheit; but some of the stars are several thousand times hotter still. So that the amount of Energy confronting us in Space is majestic. How can it be accounted for? Only by the interchangeability of Energy and Matter. Where there is Matter there is sure to be Energy. There is no difficulty at all in accounting for it on the lines here indicated. And if ever the human race get hold of a means of tapping even a small fraction of the Energy contained in the atoms of their own planet, the consequences will be beneficent or destructive according to the state of civilisation at that time attained, and the beneficence or malevolence of their spiritual development.

CHAPTER V

ON DISCONTINUITY IN GENERAL

THE two outstanding novelties which the present century has introduced into theoretic Physics are the mathematical method of Relativity and the detection of an essential discontinuity in dynamic processes concurrent with the interaction between Ether and Matter, especially those concerned with the internal structure of the atom and its radiation.

People in general have not yet realised that the recently introduced physical constant, the *Quantum*, is quite as important as "Relativity." That Relativity in skilled hands is able to yield surprising and interesting results is true. But then the quantum is able to yield interesting results too, and in a more simple manner. Whatever may ultimately turn out to be true about Relativity considered as a philosophy, there is no doubt that the introduction of the quantum into Physics represents a real though not ultimate fact. That is to say, experience shows that the fact is there; although we have at present no explanation of it. And the elucidation of the structure of the atom, to which the quantum has led, is one of the most extraordinary and illuminating and momentous discoveries in twentieth-century Physics. By aid of the quantum we now know, at least empirically, a large amount about what is going on in the interior of an atom, and many details about its vast store of energy.

What then is a quantum? It originated in a discovery by Professor Max Planck, of Berlin (beginning in the year 1900, and becoming established more and more strongly during the next twenty years), that radiated energy in the form of light or *X*-rays went about in packets or indivisible units—like cartridges, any one of which represents a store of energy, and any one of which can liberate that energy and produce an effect—but of which no fractions were possible. Why the radiation emitted by atoms should thus be distributed in packets is not yet fully known; but we are certain that it has something to do with the internal structure of every atom. And we are now prepared to admit that an unexpected discontinuity, running through the whole of atomic science and therefore essentially through the whole theory of matter, has been discovered.

In regions where continuity had been thought to reign—everything smooth and flowing and continuous and regular—an abrupt discontinuity has made its appearance, replacing the smoothness by a jerk, the flow by a precipitous jump, the continuity by a succession of steps. Regularity and law and order remain. Everything is perfectly regular and law-abiding, and yet discontinuous or occurring in steps. Not that the steps are all equal. They constitute a graduated series; but they are perfectly regular and obedient to law. Most atomic phenomena are represented by whole numbers, and not by fractions.

Discontinuities in Ordinary Life

There is, after all, nothing foreign to our ordinary notions in this recognition of discontinuity, that is to say, of units which must be taken as a whole and of which no fractions are permissible. We are familiar with it in coins of the lowest denomination. We are equally familiar with it in a staircase, instead of a slope or inclined plane; we must ascend or descend a step or several steps at a time, we only stumble if we try to take half a step.

The whole elementary operation of "counting" involves a recognition of some obvious kind of discontinuity. We can count apples or cherries; and though it is true we can divide them, that is not the way in which they present themselves to our notice: they naturally occur in quanta. So do seeds. And this illustrates different kinds of units. We may count atoms, or we may count the electrons in an atom. So we may count strawberries, or we may count the little yellow seeds upon a strawberry. Both units can be dissected, if we want to, or know how, but both present themselves as natural units.

Again in games, a discontinuity is familiar. In golf you either make a stroke, or you do not. There is no half stroke. And what is called " giving a half " merely means cancelling an opponent's stroke at alternate holes. So again the ball is either in the hole, or not. Its path is continuous up to the end, and then it drops—or else it does not. It would be possible to follow the path continuously to the bottom of the hole : the discontinuity is never ultimate; but the end is discontinuous for all practical purposes, and the definiteness is satisfactory. In games on deck, shuffleboard and others, where something slides over chalk-marked boundaries into numbered squares, some convention has to be employed to determine whether the slider is or is not within a certain area; and there may be disputes. In bowls, also, the distances from the Jack vary continuously, and may have to be carefully measured. The fall of the bails at cricket gives the required definiteness, and so does an ordinary " catch "; but " leg before " and " stumped " and " run out " are less satisfactory, for they depend on relative positions of a continuously varying and therefore less clearly determinate kind. Most games aim at quanta which can be counted. One cannot gain half a trick at whist. And the net in lawn tennis is intended to introduce an unmistakable discontinuity—the failure of which is allowed for by an uncounted " let."

The difficulty of exact counting in many cases turns mainly upon what shall be reckoned a unit. To count the pebbles on a gravel walk would be sure to raise a question as to what constitutes a pebble. And a flight of irregular worn-out steps are not easy to count, for the same reason. Counting cannot be applied to a continuous quantity except by subdividing it into artificial units. Thus it is that temperature is expressed in degrees, time in seconds, distance in feet or miles, current in ampères, electromotive force in volts, and so on. By this division of artificial units numerical specification is possible. But there are certain things of which the units are not artificial but natural, and strange to say electricity is one of them. And fortunately the atoms of negative electricity are all, so far as we know, exactly alike, and therefore can be counted with accuracy. Whenever we come across things that can be counted, in the unseen and ultra-microscopic region of nature, it is a sign that we are on something important and intensely interesting. Hence the Electron and the Quantum, however they may be ultimately analysed and resolved into entities still more fundamental, dominate modern twentieth-century Physics.

The " quantum " itself is not to be understood as a mere vague discontinuity, like the examples employed to illustrate one of its features : it is a definite and precise natural constant capable of being measured with precision, and it is associated with the angular momentum, also called moment of momentum of an electron revolving inside an atom.

This term angular momentum or moment of momentum is specially applicable to things that are revolving; like a fly-wheel, or like the moon. Some explanation and illustration of it will be given in the next chapter.

Why the angular momentum of a revolving electron inside an atom should have this singular discontinuous numerable quality, no one has as yet succeeded in explaining. The fact, discovered by Professor Niels Bohr of Copenhagen, has to be accepted unexplained. But then no one has succeeded in explaining why electricity itself, instead of being continuous, as used to be thought, should exist in little indivisible particles. And indeed it hardly occurs to most physicists that an explanation is wanted : they are usually content to accept the fact, on thoroughly substantial evidence.

So it is with the world in general when people contemplate the stars. It probably does not occur to many to consider why matter should be distributed in spherical masses scattered about in space with immense intervals between them, instead of being aggregated into one great lump under the influence of gravitation. Certainly it is far more *interesting* to find all these myriads of separate bodies, most of them of the same order of magnitude as the sun, with smaller attendants, on the surface of which we and other discontinuous creatures can live; but only recently has it occurred to Eddington and other astronomers to speculate on the reason for this discontinuity in large scale matter; which may be said roughly to imitate in a gross manner the atomic discontinuities of every visible and microscopic speck.

Bodies may be much smaller than the sun; but then they will not be permanently hot enough to emit much light. We might then only see them as we see meteors when they enter our atmosphere and are ignited by friction, as "shooting stars." On the other hand, if bodies are much more massive than the sun, it is found that they must tend to break up. Too massive a body, subject to its own gravitation, would not be stable: it would easily separate into two. Accordingly any number of double and even multiple stars are known. When divided, the two components will tend gradually to separate, by reason of tidal action, in a way which is understood, though by no means obvious. So gravitation does not pull everything together, but indirectly tends to drive things apart. The earth and moon, for instance, are believed on good evidence to have once been a single body. But the moon having budded off, from a now nearly filled-up scar in which the water that has accumulated is called the Pacific Ocean, has gradually receded, in an age-long spiral path; and is still very slowly receding; because of the reaction upon it of the terrestrial tides which it helps to generate.* (Briefly we may explain

* See, for instance, the concluding chapter of my *Pioneers of Science* (Macmillan).

that the pull of the tidal wave on the moon, as the vast low protuberance is carried forward by the rotation of the earth, tends to accelerate the moon tangentially; and that has the effect of making it go further away. Retardation, on the other hand, would tend to bring it nearer; for if it were stopped altogether, it would merely drop in.)

A dropping towards the centre, in the case of a revolving electron, is actually experienced, and is the chief source of emitted radiation and of bright line spectra. Conversely, absorption of radiation can be the means of removing an electron from an inner to an outer orbit, or even of flinging it away altogether. Radiation is emitted, and seems also to be absorbed, only in quanta. All photoelectric phenomena (which are rather extraordinary) are regulated by the quantum, and without it are inexplicable. An explanation of photographic activity, and probably of retinal vision, is to be sought along these lines. All these things represent interaction between Matter and Ether. The sciences, Physics, Chemistry, and Physiology, here meet and interlock.

On September 16th, 1899, Sir J. J. Thomson, summarising in masterly manner the results of two years' previous work, announced to a joint meeting of the Physics Section of the British Association at Dover, in the presence of a contingent of the corresponding French Association simultaneously meeting at Boulogne, his isolation or individual detection, in a Crookes stream of cathode rays, of apparently indivisible corpuscles much smaller than the atoms of matter; or, in other words, he described his experimental realisation of the "atoms of electricity," the existence of which Faraday and Clerk-Maxwell had more than half suspected, and which had been named in advance "Electrons" by Dr. Johnstone Stoney. The discovery of these natural electric units has revolutionised the treatment of all departments of Electrical Science.

A few years before (in 1896), Zeeman, of Amsterdam, had ascertained that electrons of small mass were the particles which radiated energy from an atom; and H. A. Lorentz, the very eminent ex-Professor of Physics at Leyden, had showed mathematically that, assuming the radiating particle to move in an orbit, it would be perturbed in a calculable manner by a magnetic field; and, in accordance with the theories of Larmor and himself about radiation, he was able to predict thereby many detailed phenomena concerning the observed magnetic subdivision of spectral lines and their polarisation; a set of predicted phenomena which Zeeman forthwith confirmed experimentally.

The fact that whirling electrons constitute a magnet, and this other fact that a magnet acts in a certain way on a source of light so as to modify its spectrum, have enabled Professor Hale in California, with great skill and splendid appliances, to investigate the magnetic phenomena of the solar spots, to show that they are electronic whirls on a huge scale, and to work out some singular details of their behaviour of the utmost interest and importance.

On December 14th, 1900, Professor Max Planck, Professor and sometime Rector of the University of Berlin, announced to the German Physical Society his revolutionary theory of black-body radiation, which carried with it the discovery of an apparently indivisible unit of radiation energy, strictly proportional to the frequency or vibration period of that radiation; and thus introduced his new universal constant—the ratio of radiation energy to radiation frequency—now known as the quantum. This incipient discovery was consolidated and extended and made more credible subsequently, by the finding of Einstein in 1907, and of Debye in 1912, that the same unit occurred in many apparently diverse phenomena connected with atoms, such as "atomic heat," and could be applied to the vibration of atoms in general, even in a solid. A discovery which bids fair to revolutionise the treatment of molecular Physics generally.

Thus the twentieth century was heralded by these two momentous discoveries—the electron and the quantum—and by the consequent intrusion of an element of discontinuity into all its problems.

It should not be supposed that the idea of ultimate continuity is thereby interfered with or discarded, but it is relegated to an ultimate and not a proximate position. In dealing with masses of matter, as in the old dynamics, effective continuity reigned and still reigns, in spite of atomic theory. For instance, the science of Hydrodynamics treats water as a continuous fluid, though we have long known that it had an atomic and therefore a discontinuous constitution. But so long as we are dealing with groups of millions or billions of atoms, such as the minutest visible drop must contain, the ultra-microscopic discontinuity does not matter. Gases can be dealt with in either way. Pneumatics considers them in the gross. The Kinetic theory deals with the particles individually or statistically.

As soon, however, as we study the phenomena of radio-activity, and begin to penetrate into atomic interstices and consider the atoms individually—especially if we analyse the atom into the almost infinitesimally small electrons which compose it, and deal with these atoms of electricity—the older methods of dynamics, though still applicable to a large extent, show signs of incompleteness. They require to be supplemented by a recognition of certain clear evidence of discontinuities—in the form of jumps or steps—which, whether or not they are ultimately resolvable into continuous processes, must for a time be dealt with as what they appear to be, and must be recognised as corresponding to some real and genuine property characteristic of such atomic phenomena as we are able to observe. For these atomic phenomena show no obvious sign of continuity with the rest of physics, and prove themselves experimentally to be almost independent of all ordinary physical conditions such as we summarise under the heads of temperature and pressure. These are statistical terms, only suitable for dealing with matter in the gross. It is when dealing with individual atoms that we encounter discontinuity.

Gradually we are beginning to understand more and more about the mechanism of this marvellous universe; and it is instructive to find the same law and order ruling everywhere—inside the atom and in the remotest depths of space. In so far as there are differences in the region of the infinitely small—in so far as phenomena are found there which are not found in the region of the infinitely great—those differences, of which so far the quantum is chief, are bound to become highly instructive and are already of exceeding interest. They, and other peculiarities connected with the excessive speeds with which radioactivity has familiarised us, are beginning to dominate twentieth-century Physics.

CHAPTER VI

THE QUANTUM IN GENERAL

A DETAILED attempt to explain how the quantum enters into many parts of Physics, and how it has revolutionised the theoretical treatment of certain familiar phenomena, is beyond the scope of this book. It must suffice to say that when Matter is dealt with in the mass, and when the Ether is dealt with in bulk, the quantum is not necessary or applicable; the ordinary considerations of dynamics and optics then serve sufficiently well, or indeed to all appearance perfectly. The quantum tends to intrude when we deal with the interactions between Ether and Matter, as when Matter radiates or absorbs energy from the Ether, at least when that emission and absorption are dealt with in a minute and intricate manner. And it also intrudes when the atom of matter is dealt with specifically and individually, and even when a group of atoms is treated, not as a mere crowd, but as a crowd composed of individuals, which individuals have an average of properties which must be specifically attended to.

It has gradually become clear, throughout the twenty-four years of the present century, that the discontinuous character of the constitution of the atom involves a corresponding discontinuity in all its relations with the Ether. An atom cannot emit or absorb *any* kind of vibration, but it can emit and absorb a vibration of the right kind in a surprisingly efficient manner, with consequences that were unexpected, and which still cannot fully be accounted for. But we must learn from the facts.

In order to understand all this would require a treatise on the facts themselves; and the subject is hardly ripe as yet for popular exposition. A theory is truly not complete until it can be expounded; but then confessedly the theory is not yet complete. Experts can deal with it in a remarkable and brilliant manner, but no one else at present can hope to touch it. All we can do here is to indicate the general nature of the peculiarities that have been discovered, and exhibit the kind of difficulties which remain for further elucidation.

We may therefore take a sort of acoustic analogy; remembering that in sound the vibrating body is a considerable mass of matter, like a bell or a plate or a string or a column of air, and that accordingly quantum considerations do not apply to sound. When a string or a plate is vibrating, it is possible to detect its vibrations, without using our ears, by putting scraps of paper on the string or grains of sand on the plate; and then, when the thing vibrates, these little riders or grains of sand are thrown off or begin to dance. A familiar experiment is to suspend, in contact with the prong of a tuning-fork, a wooden ball or pellet, which is flung away when vibration begins. If now we imagine an assemblage of quiescent tuning-forks of different sizes, and a sound wave falls upon the assemblage, only those forks will vibrate which are in tune with the wave—that is, which have the same frequency—and from them the pellets will be thrown off; but until the right frequency is reached, nothing happens.

Something of the same sort occurs among the atoms of matter, at least when those atoms are free enough to vibrate individually, and are not packed together tightly into a mass. When light of a certain frequency falls upon a specific atom, the fact that it responds is indicated not only by absorption of the light, but by its flinging away an electron; the phenomenon being called photoelectricity. But the light must have the right frequency, or nothing happens. If, however, light of still higher frequency is employed, that will still serve as a stimulus, and at a certain stage there will be another response. And so, as the scale of frequency is ascended, there will be a number of responses or excitations at definite stages, showing that the atom has in its constitution definite vibration possibilities, which can respond to appropriate ether waves.

Conversely, if by any means these vibration possibilities

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are excited and made actual in the atom, radiation is emitted. But it is not emitted continuously: the emission occurs as if by a series of steps, first one and then another, as the upper portion of the staircase is reached. And unless these definite vibrators are aroused, nothing at all will be emitted. Each free atom accordingly emits its specific kinds of radiation, and no others. Thus when we come to analyse gaseous radiation by spectroscopy, we find it distributed in definite sharply defined regions of extremely small breadth, which are known as "lines." These are the famous lines of the spectrum, originally discovered by Fraunhofer, explained by Stokes, extended by Kirchhoff and Bunsen, and now forming the basis of the great and increasing science of Spectroscopy. The spectrum is discontinuous, corresponding to discontinuities in the atom.

We have called those discontinuities "vibrations," likening them to a series of tuning-forks, each with its particular note and no other. But that is only a rough analogy, and must not be pressed or believed in; for the tuning-fork responds by resonance, which the atom apparently does not. There is some kind of discontinuity, we do not exactly know what. It seems more like a jump or drop down a precipice than an ordinary vibration. But, whatever its nature, it has one result rather similar to our tuning-fork illustration, namely, that when radiation of the right frequency is absorbed, an electron is flung away: the strange thing being that the energy with which the electron is flung away is dependent on the frequency of the light which has caused its ejection. The energy is dependent, not on the energy of the light, but on its frequency or inverse wave-length. The energy of the ejected electron must have come from somewhere; but it does not seem to come from the light, and in that respect the photoelectric effect is quite different from the rough acoustic analogy.

The light may be exceedingly feeble, purposely made so feeble as to be hardly perceptible, and yet, if it is of the right frequency, the fully energetic ejection will be made. The electron flung away will have just as much energy as if the light had been strong. The only difference is that if the light is weak, the number of electrons so ejected from a crowd of atoms will be few; whereas if the light is strong, they will be many. The intensity of the light only determines the number of ejections: it has nothing to do with the energy of each.

Hence it would seem that the energy must come from the atom itself, as if the light only pulled a trigger or precipitated a catastrophe which otherwise was on the point of occurring. A stone balanced on the edge of a precipice might be flung over by an almost infinitesimal disturbance: and the blow it struck on reaching the bottom would be quite independent of the stimulus which precipitated the drop. That seems a rather close analogy with what is happening in the photo-electric case. Light of a certain frequency is somehow able to bring about a sudden change—of a strength which has no relation with the strength of the stimulus. But the remarkable and surprising thing is that the energy of the change is proportional to the frequency which brought it about. If the stimulus is like a high-pitched note, very high up in the spectrum, the resulting energy of the disturbance caused is considerable. If, on the other hand, it is like a low-pitched note, deep down in the bass, the energy of the stimulated disturbance is but small. But in all cases the two are proportional. So that if we divide the energy of the precipitated disturbance by the frequency of vibration of the stimulating or trigger-pulling etherial impulse, we get a *constant*. And this "constant" applies not only to all the possible discontinuities in a single kind of atom, such as a sodium atom or a hydrogen atom; it applies to every kind of atom. The constant ratio between energy and frequency, as above defined, is not limited in its constancy to one particular kind of material. It is a universal constant, and therefore of the highest possible consequence and importance! It is the constant first dragged to light by Max Planck, the constant which is known as his universal Quantum.

The magnitude of the quantum, which everyone has agreed to denote by the letter h, is very minute; it is only discoverable in the internal recesses of the atom; it is masked and obliterated when we are dealing with matter in the lump; but it has an importance to those who are studying the interactions of matter and ether which can hardly be over-estimated.

This constant h has been applied by a multitude of investigators to all the relevant parts of Physics, not only to photoelectricity and atomic radiation and the structure of the spectrum, but also to the general relations between temperature and heat; in fact to every department which had been previously obscured by the erroneous though attractive hypothesis of the so-called equi-partition of energy between all possible degrees of freedom. It used to be taught that when a system of particles so numerous that they could only be dealt with statistically or on the average—when such a system received energy, that energy would very soon be distributed and shared equally, on the average, between every kind of motion possible to the constituents of the system. The theory was initiated by Clerk-Maxwell; and in the form he stated it, it was true. A great number of elemental rigid molecules flying about indiscriminately do share their energy equally: each molecule on the average soon acquires and possesses the same energy, whether it be hydrogen, oxygen, nitrogen, or what not. Each molecule also shares its energy equally, on the average, among its obvious degrees of freedom—that is, among its possible motions of translation and revolution in the three dimensions of space. For spherical molecules the number of possible motions is 3 (up and down, to and fro, right and left). For dumb-bell molecules the number is 5, because two effective rotations may be excited as well. For triple and multiple rigid molecules the number is 6, because rotation about a third axis may now be caused by the collisions or so-called impacts. It was not so with a dumb-bell. But when internal vibrations are attended to, in non-rigid molecules, and still more when each atom was found to have a complicated internal structure, and when the interaction with the ether was taken into account, it was perceived that this law must have limits, even though the motions and interchanges were taking place at perfect random—as required by the theory.

It is to be noted that internal law and order would militate against any simple application of the law. It does not apply or attempt to apply to the solar system, for instance. Similarly, it may not apply to the constituent system of an atom. There can not possibly be equal sharing among all the apparent degrees of freedom; for the energy would then be frittered away in such innumerable parts that none of them would contain anything worth mentioning—which is obviously not true. When heat is added to a body the temperature does rise, the capacity is not infinite; except when change of state is occurring, for then the molecular configuration is known to be changing, and the degrees of freedom are innumerable. Heat added to ice does not raise its temperature; heat removed from freezing water does not cool it. Heat removed from iron at a certain critical point may actually raise its temperature. The same paradoxical condition of things occurs in the sun and stars: at certain stages the more heat they emit the hotter they get. But these are peculiar exceptions; and none of these considerations apply to atoms. Their actual degrees of freedom are found to be limited in number, and at really low temperatures are quite few. The heat capacity of atoms is definite and known: there is a great constancy about it when properly measured. Certainly the energy is not subdivided among innumerable degrees of freedom.

One way of getting over the difficulty was to say that most of the conceivable modes of motion must somehow be impossible—that higher vibrations, for instance, cannot be excited—and that the theory should only be applied to those few which actually occur.

Well that, in modified and rather more definite form, is what the quantum theory asserts. The internal atomic catastrophes which represent and correspond to radiation energy are only capable of stimulation under certain conditions; and those conditions have taken a definite and unexpected and most interesting form, the full meaning of which future generations of Physicists must unravel. Meanwhile there are excellent Articles, "Quantum Theory" and "Radiation Theory," by Professor C. G. Darwin, in Vol. IV of Glazebrook's "Dictionary of Physics," which professed students of Physics would do well to study in detail.

CHAPTER VII

MODES OF INVESTIGATING THE ATOM

Before going further, it may be asked, very reasonably, whether any idea can be given of the methods whereby the constitution of the atom was investigated, and how the measurements were made and the counting of ingredients accomplished. In a general way, it was done by means of Radioactivity and *X*-Rays in conjunction with the Spectroscope. A spectroscope analyses the waves emitted into the ether, and thereby throws light upon the structure which produced them; much as the ear analyses waves in the air, and enables us to specify the emitting instrument as a clarionet, or a harp, a violin, or an organ. *X*-Rays are only higher octaves of radiation, akin to those of visible light; and though the eye cannot perceive them, save very indirectly by their effect on matter, the photographic plate registers their effect in so material a manner that analysis of these terribly high frequency waves has become possible, and has taught us a great deal.

When a discovery of the first rank is made, it is bound to have consequences beyond what anyone could possibly anticipate. Radioactivity was such a discovery, whether we regard the spontaneous variety discovered by Becquerel and extended by Madame Curie, or whether we contemplate the artificially excited variety, discovered so sensationally a few months before by Röntgen. That *X*-rays might be used in surgery, and possibly even in medicine, soon became obvious; but at first no one could have expected that these rays would give us a means of exploring the innermost secrets of atomic constitution. Nevertheless, within less than three years of their discovery, their ionising power was utilised, by J. J. Thomson, Rutherford, Barkla, and Townsend, to turn rarefied air into an electrolyte, and, by determining its conductivity and in other ways, to help measure the atomic charge of electricity. Since then Moseley and others counted the electric constituents of atoms by their means.

This statement is too brief and imperfect to give any idea of the nature of the problem solved. With the utmost brevity we can expand it thus: The magnetic deflection of cathode rays gave a measure of the electrochemical equivalent of negative electricity m/e. The energy gained by falling down a known potential gave the electronic velocity v. Next, the current intensity $n\,e\,v$ was determined in gas ionised by X-rays, and again subject to a given voltage. And then a cloud of vapour was condensed round the ions, the water in the cloud being weighed, and its rate of fall measured. This last, by Stokes's theorem, gave the size of the drops, and therefore enabled the drops, and so the ions, to be counted, so that n was determined. The separate determination of these quantities, m/e, v, $n\,e\,v$ and n, gave us the fundamental electric unit e, and a first approximation to the surprisingly small mass of the electron m. Most of these papers were published in the *Phil. Mag.* during 1897 and 1898; and thus the previously suspected electron was brought out into the light of day, and the nature of cathode rays was demonstrated. I have dealt with these matters to some extent in my book "Electrons" (Bell & Sons).

But what were the X-rays? It was some time before we knew for certain what these rays were. Some thought they were flying particles; others, including Röntgen for a time, thought they might be longitudinal waves in the ether, analogous to the waves of sound in air; while others again thought that they might be pulses or vibration shells of extremely high frequency—very short waves in fact—of the usual transverse type, constituting a great extension in range, but not a fundamental difference in kind, from the regular visible and ultra-violet spectrum. It is noteworthy that the passage of such rays in straight lines, without refraction by matter, had already been provided for in Helmholtz's "Theory of Dispersion"; for it was therein shown that as the waves got shorter and shorter, the deflection or dispersion, which had at first increased, would cease to increase and begin to diminish—the spectrum would, so to speak, be folded back upon itself—so that waves which were smaller or of shorter period than any of the dispersing particles would not be deflected at all, but would continue along their original path.

I and many others made attempts to deflect or analyse these rays by obtuse dense prisms, by prismatic magnetic fields, and by metallic or transparent gratings—without result. What we did not do was what Laue and the Braggs did so splendidly later, namely, use the fine molecular stratifications inside crystals to produce the required cumulative dispersion effect; and so to obtain, with the co-operation of Moseley and Darwin, first diffraction effects, and finally an *X*-ray spectrum—the latter being made photographically clear and definite by Owen and Blake in 1913. Directly *X*-ray spectrum analysis was achieved, something might be expected to happen; and it was anticipated that information would soon be forthcoming about structures almost infinitely minute.

So it turned out, and the way in which *X*-ray spectra illuminated the internal structure of atoms is now our theme; beginning with an apparent digression.

Spectrum Complications

In my youth, when the study of spectrum analysis was in its infancy, though it seemed simple enough at first to say that a definite line belonged to and indicated a definite substance, the phenomena, as they were studied, became far more complicated than that. The number of lines which could be obtained even in the visible spectrum, by the use of arc and spark, seemed almost innumerable; so that spectrum analysis, as a practical method of investigation, seemed likely to kill itself by its own complexity.

Then it was found that even a really simple spectrum like that of hydrogen was only one of a series, and that in the ultra-violet and infra-red regions there were other series. How could the hydrogen atom be simple if, when it vibrated, it gave such a complicated series of wave-lengths—like a whole series of notes in music; not even a simple series like those given by a stretched string or an organ pipe, but a compound clang like a struck metal plate, or as if someone sat down on the keyboard of a piano?

So it used to be thought that an atom must have a very complicated structure. And as my brilliant teacher of more than half a century ago, W. K. Clifford, used to say: an atom must be at least as complex as a grand piano. Or as someone has quite recently said: To try to make a model of an atom by studying its spectrum is like trying to make a model of a grand piano by listening to the noise it makes when thrown downstairs.

Well, there is truth in the exaggeration. And anyone looking at a modern spectrum map, with uninstructed eyes, might well marvel that it contains any indication of the structure of the atom which has emitted all those lines, and that that structure is not so frightfully complicated after all. Complicated it is, but not hopelessly so. The simpler atoms have been reduced to law and order already. The others will succumb to the labours of the remarkably brilliant present generation of physicists; or so it seems likely. The key was put into our hands when the electrons in the atom were counted, and when it was found that hydrogen could possess only one. With one attracting centre and one revolving electron, obedient to the law of inverse square in accordance with Rutherford's demonstrated view, the hydrogen atom could not possibly be complicated; not so complicated as earth and moon; for the great perturbing body, the sun, is absent. Unless indeed an outside electric or a magnetic field is applied, when things do begin to get a little confused; though even then there is no real confusion, but only a rather more complicated, but understood, series of lines.

Apart from perturbations, however, how is it that a hydrogen atom, with only one electron, can emit all the lines it does? The question was not answered till Bohr answered it. And he answered it in terms of Planck's quantum. He said, virtually, that though there is only one electron, it may have alternative orbits. Not every orbit is possible, but only some; which he specified as possible on the assumption of the quantum. He said further that radiation was emitted when the electron dropped from one possible orbit to another, and not otherwise; and that the particular rate of vibration emitted depended both on the orbit it dropped from and the orbit it dropped to. This, once granted, as he showed, was able to account for everything, so much so that it is now universally admitted.

Thus ingeniously the hydrogen atom retains its intrinsic simplicity, mingled with a certain kind of potential complexity. There is only one electron, but it has a choice between many different orbits. It is not tied to one, even in the same atom. And if the atom is given plenty of room, and not jostled, it has a choice of thirty orbits, or more. If it is in any but the innermost one, it is liable to drop. It is as if a moon or a meteoric stone, circulating round the earth, could sometimes drop a few thousand miles and take up a fresh position. Ordinary astronomy is simpler than atomic astronomy: these violent cataclysms, due to a choice of potential orbits, do not seem to occur on the large scale. Why the planets have chosen the orbits they have is not known. But, fortunately, they adhere to those they have chosen.

But how in the world are all these things ascertained about the atom? The answer is: Primarily by the use of *X*-rays, that is to say, by making use of their exceedingly rapid vibration and ultra-minute wave-length.

A model atom had seemed impossible, for it had long been taught that molecular and atomic constitution were on too small a scale for examination or analysis by any direct method analogous to vision. In other words, it was considered hopeless that we should ever, in any sense, *see* these structures; because the instrument by which we could see them, namely light, though its waves were exceedingly small for ordinary purposes, was hopelessly too coarse an instrument to exhibit the details of atomic structure. The most visible waves were 5000 or 6000 atoms in length; and though, by the use of ultra-violet radiation and photography, it might be possible to shorten them, ten, twenty or even a hundred-fold, it seemed unlikely that we should ever be able to discover and employ radiation of an altogether smaller order of magnitude.

By the use of crystals, however, the wave-length of X-rays could be measured, and was found to be as small as atoms, or even smaller. And since these small waves still fortunately retained the power of reducing the silver salts on a photographic plate (which surely is itself a remarkable fact), it was clear that a probe, or means of penetrating the secrets of the atom, was put into our hand.

To use such a probe, however, and to interpret the results obtained, demanded great skill and a spark of genius. Even to get results at all required skill, but it would have been comparatively easy to go on accumulating more or less unintelligible results, without detecting their inner meaning and deciphering the lesson they contained.

Fortunately, this is not what happened. The genius of Moseley was adequate, both for the experimental exploration and for the theoretical interpretation. Splendid work was done at that time in Manchester, as well as in the Cavendish Laboratory, and one of the special features of all this work has been that experiment and theory have gone hand in hand, sometimes one a little in advance of the other, but never wholly outstripped; sometimes the theory a little askew, but nevertheless trending somewhat in the right direction, and able to be straightened out by further work elsewhere, the residual un-withdrawn bulge being hardly noticeable, and not really obstructive, as time went on.

The Moseley work showed that the atoms of the chemical elements stepped by equal differences in regular arithmetical progression, from the lowest to the highest. And, assuming a nuclear constitution, Moseley concluded that the step each time must be the addition of a positive charge to the nucleus. His words are :—

> "We have here a proof that there is in the atom a fundamental quantity which increases by regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus."

Thus he surmised that the indivisible unit of positive charge—which itself is a kind of quantum and is known to be numerically equal to the indivisible unit of negative charge—was the step by which each element differed from the one below it. And reasons could be given for asserting that this same step constituted the difference between the lowest of the elements and nothing material at all. In other words, that the series or staircase began with 1 in rising from the ground level 0, and ascended by equal steps to 92, or—as some hope, without as yet adequate foundation for the hope—to 118.

Since then we have learnt that each step of the staircase is liable to be occupied by more than one element; elements which differ in weight, and sometimes differ sufficiently to have different names attached to them, though in chemical and spectroscopic qualities they are remarkably alike. And we have also learnt that each element, as hitherto known and recognised in chemistry, is not necessarily limited to one step, but is liable to be scattered about on several steps. So that, taking its average position, as indicated by its atomic weight, it might seem not to be on a step at all, but on some intermediate non-existent fractional shelf or stool.

The existence of this chemical or atomic staircase pushes discontinuity into the heart of the atom of matter, and makes us ready to recognise the existence of discontinuous quanta, even in places where we cannot as yet rationally account for such discontinuity.

We must be careful not to extend the idea of discontinuity gratuitously into regions where it does not apply, and where we have no valid excuse for suspecting it, such as into Space and Time and other abstractions. But we need never be surprised at its occurrence in connection with electricity and matter, and especially with phenomena dependent on the interior of the atom.

Discontinuous Mechanics

It is a mistake to suppose that the discovery of the quantum replaces or in any way negatives ordinary mechanics. The laws of mechanics hold, but they are supplemented by a numerical discontinuity of a very remarkable kind, which evidently owes its origin to the discontinuity discovered in electricity, that is to say, to the electron and the proton, the discontinuous units of which matter is composed. This discontinuity extends surprisingly into the space immediately surrounding them, so that of all the infinite number of orbits which might have seemed possible, only a few, definitely associated with integers, are stable. These, therefore, are the only ones which can be permanently occupied by a revolving electron, and radiation only occurs when an electron drops from one to another of them. A study of spectra enables us to specify the pair of orbits between which the drop occurs. Stable orbits are called energy levels. Radiation is emitted when an electron drops from one level to another.

The disturbance caused by *X*-rays, or ultra-violet light generally, raises or jerks up an electron from a lower to a higher level, thereby enabling it subsequently to drop when the atom rearranges itself after the luminous stimulus has been withdrawn, or even during the continuance of the stimulus. *X*-Rays usually eject an electron altogether, or in other words ionise the atom, throwing it away to infinity, that is to say, to a distance comparable perhaps to the 1/10th of a millimetre. But another one soon enters, and, in settling down into its proper position to restore the perturbed configuration of the atom, emits a flash or shell of radiation analogous to the *X*-rays which produced the perturbation. Bombardment by particles also produces the same effect, if they are quick enough, that is, if they have sufficient energy. And accordingly a cathode-ray bombardment also excites *X*-rays when they strike the atoms of a target.

(Fig. 1 shows the ionisation by an *X*-ray beam ejecting electrons from atoms of gaseous matter. Fig. 1 can be compared with Figs. 2 and 3, which are referred on p. 85).

But the *X*-rays so emitted need not consist of a definite and characteristic radiation only. Intermingled with the characteristic rays are others which may be called random rays, due to the miscellaneous bombardment of molecules, so that the spectrum emitted is partly a continuous spectrum. But the characteristic radiation proper to the atoms of the target is superposed upon it, giving definite bright lines indicative of characteristic and definite frequencies. It is these bright lines which represent a drop from one stable orbit to another, or from infinity into one or other of the stable orbits; the innermost orbits naturally giving the highest frequencies. The highest frequency possible from an atom is given by an electron dropping from infinity into the innermost or *K* orbit. This is the one that emits the shortest wave-length. But in order that radiation of this shortest wave-length can be emitted, the ionising disturbance must be sufficiently strong, that is to say, sufficiently rapid, to have ejected an electron from this *K* orbit, so that, thereafter, in the process of re-adjustment, it may be able to drop back again. We shall become more familiar with K. L. M. orbits and energy levels, later on.

If the exciting stimulus is only adequate to eject an electron from the *L* or from the *M* orbit, then again you get the shortest wave-length which that particular stimulus is able to excite. It is not the shortest possible to the atom, but it is the shortest possible to the particular exciting stimulus. And what are called " soft *X*-rays " are only able to excite these or still more modest varieties. The kind of *X*-rays emitted from a Röntgen tube will depend on the difference of potential between cathode and target; and, accordingly, if we measure the shortest wave-length emitted, we shall get a measure of this same difference of potential. In other words, an *X*-ray spectrometer can be used as a voltmeter—which is really a remarkable fact.

Those who have much to do with *X*-rays are probably accustomed to measure the wave-length in this way, and are aware that the shortest wave-length obtained is a measure of the " hardness " or penetrating quality of the ray, whether it has been through filters or not. By this means it is possible for an *X*-ray practitioner to ascertain exactly the kind of *X*-ray which he is using, and to adapt the circumstances until he gets the kind of ray which for his special purpose is most suitable. For it is clear that too great penetrability will not bring out the contrast between the dense and lighter portions of structure examined, and thus will not give a clear *X*-ray photograph. Rays that are too soft will not penetrate sufficiently. Rays that are too hard will penetrate too much. What is wanted in *X*-ray practice is the kind of ray which will discriminate most clearly, and exhibit the fine shades of density in the material or part of the human body that is being examined. And it is very remarkable that recent progress in physics has conferred upon *X*-ray experts the means of analysing their rays and thus securing the best results. It is perhaps still more remarkable that the modern theory of the atom gives a complete account of these phenomena, and enables us to follow out the process in detail, and to say what kind of ray is to be expected from a given atom under given stimulating conditions.

The theory of the *X*-ray spectrometer is very simple: it all depends on the fine structure in crystals, discovered by Laue and by Sir William and Prof. W. L. Bragg—an example of high genius devoted to crystallographic exploration, a method which has revolutionised crystallography, and enables the structure of chemical compounds to be analysed with a thoroughness and degree of precision which ten years ago no one could have anticipated, and which is truly astonishing. Even when in solution the atoms are equally efficacious, the physical state of the body does not matter, and Dr. E. A. Owen* has quite recently contributed measurements on bodies in a sort of solution.

Theory of X-*ray Spectrometer*

I think one may say that the process employed in measuring *X*-ray wave-length began with the investigation by the late Lord Rayleigh of the colours of the opal, and those shown by the crystals of chlorate of potash, where the twinning of the crystal produced a regular stratification, what we should now call a coarse stratification, comparable with the wave-length of light. Each stratum reflects exceedingly little, but a large number of strata reinforce each other and reflect a very considerable amount of the particular wave-length which corresponds to the distance between the strata and to the length of oblique ray between them: $\lambda l = 2d^2$. The late Lord Rayleigh used to illustrate this

* See Owen and Preston, "X-*Ray Analysis of Solid Solutions* (Metals in Metals)," *Proc. Phys. Soc.*, 26th Oct., 1923.

effect by sound also. He mounted a number of muslin discs on a lazytongs, so that the distance between the discs could be readily varied by opening and closing the tongs, and he then used these strata as reflectors of sound from a bird-whistle too high for audibility. The particular wave-length was selected and reflected, and the fact was demonstrated by a sensitive flame, which responded to this high inaudible note.

The same thing, exactly, happens in the chlorate of potash

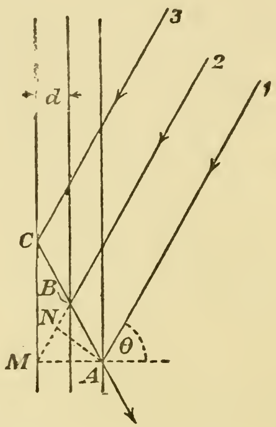

FIG. 4.—THEORY OF *X*-RAY SPECTROMETER.

Three rays reflected at the strata A B C combine at A to produce a reflected ray along the arrow if they arrive in the right phase; which requires that $\lambda = 2\,d\cos\theta$.

crystals; they reflect light of a definite wave-length, and give therefore a bright line when analysed by a spectroscope. These pure colours are also obtained from the opal, which must have a similar stratified structure. They are different from, and more beautiful than, the colours of thin plates, such as you see where oil has dropped on water; for these are due to reflection from a single film, and are by no means pure colours.

The stratifications in ordinary crystals, like rock salt, are very much finer than the comparatively coarse stratification by twinning in chlorate of potash. They are of real molecular dimensions, and accordingly they do not act on visible light at all, or even on ultra-violet light. What they thus specifically reflect is hopelessly inappreciable by the eye. They do, however, reflect *X*-rays, and that is the way we get the *X*-ray spectrum. It was by this means that Moseley was enabled to show that the *X*-ray spectra of different atoms formed a regular ascending series; as is well known.

An *X*-ray spectrometer (Fig. 4) therefore consists merely of a plate of, say, rock salt, mounted so that it can be turned through a small angle, and of a fluorescent screen adjusted to display the spectrum produced when *X*-rays fall upon the rock salt crystal. If the distance between the strata in the crystal is d, and if the angle of incidence of the light is θ, the wave-length which is reflected from all the strata at the corresponding angle of reflection θ is

$$\lambda = 2\,d\,\cos\theta$$

and no other rays but these are efficiently reflected in that direction.

The whole thing is beautifully simple in theory, and I should think convenient and feasible in practice.

Alternative Ideas of Atomic Constitution

We all know that in order to explain the intricacies of visible and ultra-violet and infra-red spectra, Niels Bohr was led to postulate the existence of energy levels—another kind of staircase inside the atom—at any of which an electron could rest or revolve in stable equilibrium, but so that when occasion arose it could drop from one level to another, and thereby emit a characteristic radiation or spectrum line. These energy levels become very complicated for the higher elements in the series, at least for visible and ordinary ultra-violet spectra. But for the much higher *X*-ray frequencies they retain most of their original simplicity, since for them we have only to do with a fall to orbits at the lower levels, where the crowd of perturbing electrons are most of them outside, with their perturbing influences removed or cancelled. It seems that the level finally arrived at by the dropping electron is the important thing. Its starting place is of subordinate, though real, importance, but the changes and chances of its pilgrimage from one position to the other exert no obvious influence on the radiation emitted.

The whole Bohr scheme of energy levels depends upon the nuclear atom—the conception that, like a solar system, the main mass of the atom is in the central positively charged nucleus, and that the electrons revolve round it in orbits, according to the law of inverse square.

But what is the evidence for this astronomical constitution? It is by no means the only law that can be devised. An atom in which the central force of attraction varied as the direct distance, analogous to an elastic instead of a gravitational control, seemed at one time more promising. For the direct-distance law, which gives a period of vibration or revolution independent of the amplitude, seemed to have a better chance of explaining sharp spectral lines. Indeed the inverse square law, where every fluctuation of distance would be accompanied by a fluctuation of period, could not account for spectrum lines at all! The possibility of spectrum lines, with such a law of force, is wholly dependent on the quantum; and that seemed, at first, a weird and *ad hoc* an illegitimate device.

Hence it was that I, for one, and J. J. Thomson, for a much more important other, favoured at first the notion of a diffuse globular charge with electrons revolving inside it; as explained in my Romanes Lecture at Oxford called "Modern Views of Matter," 1903. The other or astronomical form of atom was in our minds (I remember discussing it long ago with Prof. Poynting, who indeed rather favoured it, in spite of its difficulties), but the demonstration that it was the true atomic model—that the mass of the atom was a real impenetrable central nucleus, of exceedingly small size, exerting force as the inverse square of the distance, both attractive and repulsive—was made unmistakably by Rutherford in his brilliant development of Barkla's experiments on the scattering of alpha-rays.

Evidence for the Nuclear Atom and the Law of Inverse Square

The steps by which the nuclear atom was established are of such interest that it is worth while to remind ourselves of them. Rutherford was bombarding atoms by the alpha-particles projected with known velocities from a deposit of radium-*C*. He has carried out such bombardment many times since, sometimes with surprising and exciting results. But this time he was merely driving the particles through matter and catching them on a fluorescent screen, so as to see how many had been scattered or deflected from their original path, and by how much. If the atoms consisted of a nucleus surrounded by electrons, at planetary distances in proportion to their size, the atom would be as porous as a solar system, and the alpha-particles could be trusted to go through it, for the most part, without perceptible perturbation. Some of the electrons might be knocked out, and so the atom become ionised; but the massive alpha-particle would take scarcely any notice of minor obstructions, and would proceed untroubled on its way, until it encountered or came exceedingly close to a central nucleus, or mass greater than itself. Such an occurrence would be comparatively rare. Judging by the probable size of the nucleus, on electric theory, it would not occur more often than 1 in 10,000 times—probably not so often. These tracks, Fig. 2, photographed by the skill of Mr. C. T. R. Wilson, show an alpha particle pursuing a nearly straight path through a gas crowded with atoms, being barely deflected until they encounter a nucleus, when they are suddenly deflected or suddenly stopped. In Fig. 3 is shown the tracks of free electrons making their way through the atoms of a gas and being easily deflected, because they are so light and immaterial (see p. 79).

The circumstances of such an encounter, whenever it did occur, are amenable to ordinary and, so to speak, elementary dynamical considerations, if the law of inverse square holds good. Accordingly, it was possible to deduce beforehand what would happen in all the likely kinds of collisions—if they can be called collisions where there is no contact. The law of probability could be applied to determine the number of scatterings in each direction; and then, by the aid of Crookes's fluorescent zinc sulphide screen, on which the splashes or flashes caused by the impact of the deflected alpha-particles could be seen, the number scattered in any direction by the atoms of a given substance could be counted and compared with theory. The result was triumphantly to uphold the theory. The central solid compact nucleus was established as a reality, and a proof was forthcoming that it exerted force, even in its immediate neighbourhood, as the inverse square of the distance—the first time, so far as I know, that it was ever established that astronomical laws still hold good, even in the hopelessly ultra-microscopic region in the interior of atoms.

The problem may be stated thus. Take a massive particle with charge E—really equal to Ne, where N is Moseley's atomic number; and fire it, with known velocity v, at a much less massive particle with a charge E'—really $2e$. Consider what happens.

First let the line of fire be absolutely direct. The projectile will approach within a distance $2a$ (Fig. 5), and at that distance (SJ) will rebound and return whence it came. The distance $2a$, which we may call "the stopping distance," is important; for it gives the major axis of all the hyperbolic paths which are the result of a less direct impact between the same particles. The bipolar equation of every one of these hyperbolæ will be

$$r_1 - r_2 = 2a.$$

The value of $2a$ can be calculated at once as

$$2a = \frac{EE'}{\frac{1}{2}mv^2};$$

for that is the distance at which the kinetic energy of approach will be converted into the potential energy of recoil, and so the bombarding projectile will there be brought momentarily to rest before being driven back to its source.

In practice, absolute direct impact or accurate aim is infinitely unlikely. Let us take the case then of slightly oblique aim, so that the line of fire approaches the nucleus within a perpendicular distance b. The path will now be a hyperbola, with the above value of a for its semi-axis major, and with b for its semi-axis minor. The equation to the hyperbola being, as stated, $r_1 - r_2 = 2a$, its eccentricity is $\surd(1 - b^2/a^2)$, or what we may call sec θ. The asymptotic path of the particle will be swung round through an angle $\pi - 2\theta$, where $\tan\theta = b/a$. In other words, the particle will be reflected as if it had struck a mirror in a certain position and with a certain inclination (which can be best depicted in a diagram), and as if it had rebounded from it according to the usual law of reflection (Figs. 5, 6).

Of course, it does not really strike anything: there is no clash or blow of any kind. The path is a perfectly regular curve, as shown in Fig. 6. But all the appearance, as seen from a distance or as estimated from the result, will be as if it had been suddenly reflected, from a mirror M, according to the exact geometrical conditions of Fig. 5.

If we consider the projectile as having a sign of electric charge opposite to that of the central nucleus, so that it is attracted instead of repelled, then the circumstances will be very similar. There will still be the appearance of

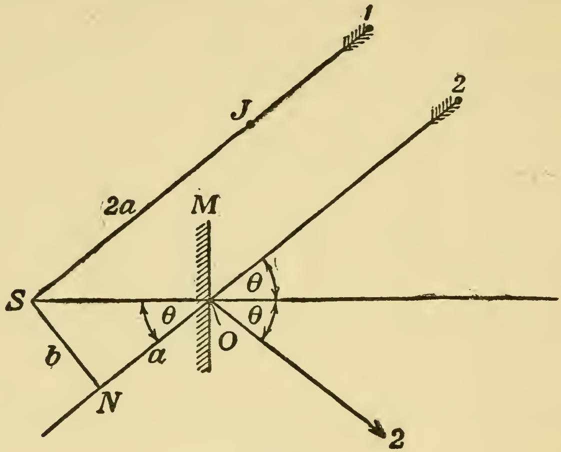

FIG. 5.

Fate of two corpuscles approaching a repelling centre of force, *S*. No. 1 is turned back at *J*. No. 2 is diverted as if reflected from an imaginary mirror, *M*, situated exactly as geometrically shown.

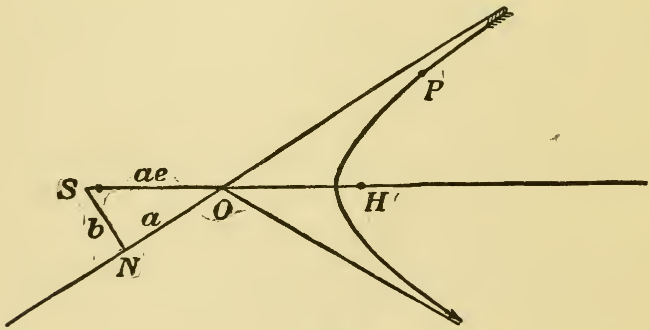

FIG. 6.

The real path of corpuscle No. 2 in Fig. 5 is here more fully shown; it is a hyperbola with the asymptotes of Fig. 5. Its path is the same whether repelled by *S* or attracted by *H*.

reflection, as in a mirror; the angle turned through will be just the same, for the same line of aim; and the same hyperbolic path will be described; but the central attracting particle will be in the other focus. H instead of S.

The accompanying figures, 5 and 6, give a good idea of what a " collision " between charged particles is really like when the inverse square law is obeyed.

And so the nuclear atom was established, in spite of the apparent impossibility of accounting for its discontinuous or line spectrum. A line spectrum indeed cannot be accounted for except by the quantum. And as the quantum has not been as yet dynamically justified, we may say that the line spectrum cannot even yet be fully explained, at least not in the way the nineteenth century used to think of explanation. The quantum, once granted, however, does astonishingly give numerical results in accordance with spectroscopic observation to a very high degree of accuracy. Any future exposition of this strange unit, the quantum, will be welcome, but meanwhile its manner of employment by Bohr has more than justified itself by accordance with fact; as we shall see in subsequent chapters.

CHAPTER VIII

APPLICATION OF QUANTUM CONSIDERATIONS TO ATOMIC STRUCTURE AND CONSEQUENT RADIATION

We must now proceed to a rather more precise treatment, and must introduce a few simple formulæ, which replace in a clear and definite manner—so soon as they are understood—a maze of words; they render calculation humanly possible, by aid of the simplicity and tractability of algebraic machinery. It must not be supposed that formulæ and equations are introduced in malice or for purposes of confusion. Once mastered, they are a delight, and full of an exact and compact simplicity unobtainable otherwise. It is a pity that so many people deny themselves the pleasure of understanding and employing them. They are indispensable to Physics and Engineering, and are becoming necessary in Chemistry and many other subjects.

Formulæ involving discontinuities, however, with symbols which represent only integer values—so that solutions proceed by distinct steps with intervening gaps—are unfamiliar to engineers and not very familiar to physicists. Nevertheless, some of the phenomena observed in spectrum analysis demand equations of that kind; and they are not easy to obtain by what is called the Classical or Newtonian Mechanics. If observed spectra were continuous, there would be no difficulty; or, rather, the difficulties would be of a customary character. But the well-known phenomenon of line spectra—that is to say, the case when the light emitted by a substance, when analysed by a prism or grating, is found to be concentrated in a series of bright lines with intervening gaps of complete darkness—such spectra as these are not tractable satisfactorily and completely by ordinary methods. And it is especially for dealing with phenomena of this discontinuous kind that the *quantum* idea has proved so useful, though it was primarily invented in order to formulate other facts of radiation. It cannot be said to explain them, because it stands in need of explanation itself, but it harmonises all the relevant known facts, and has established itself in modern physics as an undoubted reality.

How to regard the quantum as a physical entity, or in what way it can be treated and arrived at dynamically, is still an open question. That it is a definite reality, lying at the basis of a large number of physical facts, can now no longer be disputed. Hence an elementary exposition of the meaning of the quantum, so far as we at present understand it, and of the way in which the idea elucidates, or at least formulates, otherwise intractable phenomena, must be important, and may be regarded as timely.

Introduction to Atomic Astronomy

The history of spectrum analysis in its ordinary phases may be regarded as generally known. It begins with Newton's careful examination of the colours in white light as spread out by means of a prism; and continues with the subsequent detection and mapping of dark lines in the solar spectrum by Fraunhofer; their theoretical explanation by Stokes; and a great extension of the subject into the domain of chemistry by Kirchhoff and Bunsen.

The more the spectrum of the different elements was examined, the more lines appeared; until at one time the subject seemed likely to be overwhelmed by its own complexity. An element which gave a few lines when ignited in a flame, could give more in an arc, and more still in a spark; and though some of these lines could be grouped into a series—each series characteristic of a given substance—it was subsequently found that when the bounds of the spectrum were extended up into the ultra-violet and down into the infra-red, more series appeared, all still characteristic of the same substance. Why the substance should give such a multitude of lines, if the atom of matter were a simple unit without elaborate structure, was, however, far from obvious. In fact, the phenomena of the spectrum, as throwing light upon the nature of atoms and their vibrations, began to seem as complicated and intractable as the motion of the planets, comets, and other heavenly bodies must have seemed to the Ancients.

It is well known that early astronomy when it began to be evolved, went through certain well-defined periods or stages. For an account of these stages my book "Pioneers of Science" (Macmillan) may be referred to. First, the detection of an elementary scheme of fairly simple law and order, by Copernicus; though for a long time after his period the motions of the planets were only very roughly known, and their laws not even approximately ascertained. Then the instrumental period, when exact metrical observations were made by Tycho Brahé. Then the stage at which, from these measurements, a mathematical detection of more nearly accurate though quite empirical laws, running through them and characterising them, was brilliantly achieved by Kepler. And finally—though of course there is no finality—the explanation of these empirical laws and of most of the other minutiæ concerning the motions and perturbations of the heavenly bodies—some of the phenomena having been already observed, and some predicted before and in anticipation of later observation—by the magnificently elaborated Theory of Newton. Without undue fancifulness we may trace something of the same kind of history in the working out of the phenomena of radiation.

First, a general knowledge of the composition of radiation, a measure of its velocity, and a detection of the fact that it was not a material thing, but an undulatory disturbance in the ether; which we might liken to the age subsequent to that of the Greek astronomers and Hipparchus, leading up to the simplification of Copernicus; a period which will carry us as far as Stokes and Clerk-Maxwell.

Then the instrumental and precise measurements of the constituents of radiation, beginning with Kirchhoff and Bunsen, and continuing on, through Liveing and Dewar and Huggins and Fowler, to the splendid spectroscopic instruments of the present day—all which may be taken to represent in essentials the age of Tycho Brahé, with its elaborate subsequent development in observatories like that of Greenwich.

Then, about 1885 we had the first detection of a beginning of law and order running through the discontinuous series of the spectrum lines, as by that time mapped out, by the Swiss physicist Balmer, supplemented as it was by Rydberg, of Sweden, and by another Swiss, Professor Ritz, and others, and notably extended by Bohr of Copenhagen—a stage the greater part of which we can liken to the age of Kepler; for the laws first observed, though undoubtedly correct as far as they went, were purely empirical. They enabled us to co-ordinate the observed facts and recognise that there must be laws underlying them; but they gave us no direct clue to those rational laws. They stated the discontinuities in empirical form, as Kepler stated his laws of planetary motion.

In the present epoch we are living in a Galilean, or perhaps even in the beginning of a Newtonian, age, when something of the real meaning of the empirical expressions is deciphered, and when fresh series of lines can be predicted by mathematical, or rather arithmetical, treatment; though even now the cause of the discontinuities is not fully known, and something of empiricism still remains, showing that the Newtonian era is hardly begun, and that much more remains to be done. We may, however, still regard some of the achievements as being akin to those of the Newtonian era; for Newton himself left something unexplained, the solution of which we have not even yet grasped, viz., the nature of gravitation. He had to assume gravitation as an observed fact, or, rather, as a hypothetical fact which was so successful in correlating all the phenomena that it must necessarily correspond to a reality; though its ultimate cause was, and is, still unknown.

Not that I would liken any living man to Newton, any more than I would liken Balmer and his successors to Kepler; that would be presumptuous. Estimates of this kind must be left to posterity; and most likely posterity will say that, whereas in old times things were done by an individual of genius here and there, now, amid the multitude of highly qualified workers, no one man can be picked out as super-eminent, but that progress is made by the labour, intuition and genius of a number of men, all concentrating on the same problem.

It is, however, true that we have lived in an age of giants in physical science; and the work of some of the explorers is not unworthy to be mentioned in the same breath as the "Principia." It would be an invidious task to mention names. Some of them are, or ought to be, household words; they are so in the household of physicists, in such a place as the National Physical Laboratory, for instance, or in the physical departments of universities; and to some extent their names are known to the general public. Nevertheless, I think that there would be a general consensus that, if one of the quite recent names were to be picked out as suitable for mention—partly because it is a name not known to the general public, and yet one which ought to be recognised as that of a man who has already accomplished something of a striking character, full of the seeds of further development, and arousing the greatest interest among his contemporary co-workers—it should be that of the comparatively young Danish physicist, Niels Bohr, of Copenhagen. He is of course, as he would be the first to admit, standing on the shoulders of those who have gone before; and, as for the mysterious idea of the quantum, on which part of Bohr's work is based, that owes its origin to the puzzled and revolutionary insight of Max Planck, of Berlin, in his theory of radiation from a black body. Planck found that the true law of radiation could not be arrived at or expressed in terms of any orthodox system of mechanics. The connection between radiating atoms and the energy which they emitted was such as could not be accounted for by any theory of continuous emission—not even by that of Lord Rayleigh. It was found that either a definite portion of energy was emitted or none at all. There seemed to be a coin of lowest denomination, no fraction of which was permitted. If a penny were the lowest coin in circulation, then a debt could be paid in pennies; the bank would not honour cheques made out in farthings. There seemed to be an indivisible unit of energy, and any number of such units could be expended, but no fraction. The National Debt itself might be expressed in pence, and payment would have to be made in discontinuous packets or lumps like coins. True, the coin of the quantum was of very small denomination, so small that it was only by refined treatment that the discontinuous character of radiation phenomena could be detected; but still its emission was not continuous; it did not emerge from the bank like a stream of liquid metal, but in definite little pieces or solidified discs. Money, we may say, only exists in cents or centimes, and is not continuous. So it appeared to be with energy—at least, with radiated energy. If a body tried to emit less than a centime or a quantum, it could not do it; neither, in all probability, could it receive less. Energy seemed discontinuous. Why? Ah, that was a puzzle. Planck did not know; nor do we for certain; but we feel pretty sure that it has to do with the discontinuous structure of an atom, its resolution into protons and electrons. (A proton, we remember, is the unit of positive charge, as at present known, while an electron is the unit of negative.)

Certain quantitative facts are suggestive. Electricity, in the form of an electron, we now know to be discontinuous or atomic. No fraction of an electron is known; it is the smallest coin in electricity, and it can be expressed by the indivisible unit *e*, which has been measured as $4{\cdot}774 \times 10^{-10}$ electrostatic unit. The field of electric force of this unit charge, radiating in all directions through the solid angle 4π, is $4\pi e$; and this turns out to be closely related to the quantum. It is, in fact, equal to the square root of the essential and most frequently occurring quantum, which is commonly denoted by $h/2\pi$.

Again, I find that if a proton, with its mass equal to a hydrogen atom, spins on its axis like a top or flywheel, with its circumference or equator travelling round with the velocity of light, its angular momentum is again closely related to the quantum; it is again equal to $h/2\pi$ if the proton behaves like a solid sphere of diameter 10^{-13} cm. The agreement is so close that it can hardly be accidental!

Once more, if the units of electric and magnetic fields, $4\pi e$ and $4\pi m$, are multiplied together (the m being μce for a magnetic pole equivalent to the electron), so as to exhibit their interaction in the form of radiation, which is known to be an electromagnetic phenomenon governed by a product of this kind, we again get a quantity of the same nature and of the same order of magnitude as $h/2\pi$.

These hints are quite sufficient to make us look for the real significance of the quantum, not to the discontinuous nature of energy in general, but to the discontinuous nature of its emission and absorption by the atom of matter, or rather by the ultimately atomic or discontinuous electric ingredients of which atoms are composed. Such electric ingredients can deal with any number of quanta, but they cannot deal with a fraction.

The actual quantum has now been measured. It is not really energy, but is angular momentum—otherwise called moment of momentum—a thing which is not very familiar except to engineers and physicists, and which it may be well to explain.

Explanation of the Term Moment of Momentum

The momentum of a moving body is the product of its mass and its velocity. Thus the momentum of a 5-ton truck, moving at 60 miles an hour (or 88 feet per second) is 440 foot-tons per second. This is not to be confused with the work it can do, or with the energy it possesses, though the unit "foot-tons" looks like that. But whereas the energy-foot-ton is a short-hand specification involving gravity—for it specifies the load that can be raised a given height—the momentum-foot-ton has nothing to do with gravity, and is a complete, not a short-hand or technical, specification. It had better be called a ton-foot to distinguish it.

The momentum of a half-pound projectile, flying 1,600 feet a second, is 800 lb.-feet per second. The momentum of a gramme projected with one-tenth the speed of light is 3×10^9 gramme-centimetres, or 220,000 lb.-feet, or 100 ton-feet per second.

If the moving body, instead of going in a straight line, is constrained to move in the circumference of a circle of given radius, say, because tied to the centre by a steel spoke like part of the rim of a wheel, it is said to have a *moment of* momentum equal to its momentum multiplied by the length of the radius or spoke. Thus the above half-pound, if part of the rim of a flywheel 10 feet in diameter, would have a moment of momentum 800×5, or 4,000 of the appropriate units; the proper unit being a lb. multiplied by a square foot and divided by a second of time.

In symbols, momentum is $m v$, and moment of momentum is $m v r$, where r is the radius of the circle in which the body moves. It may also be written $m r^2 \omega$, where ω is the angular velocity, the angle turned through per second, or the number of revolutions per second multiplied by 2π. In this form it is called "angular momentum," though the change of name makes no difference; and the quantity $m r^2$ is called the body's moment of inertia, or the effective moment of its mass about the fixed centre.

Every geometrically-shaped body has a simple moment of inertia about its centre of gravity—the point about which it would most naturally and easily rotate. For instance, the moment of inertia of a solid disc or cylinder of radius r is $\frac{1}{2} m r^2$. For a thin ring it is $m r^2$. For a solid sphere it is $\frac{2}{5} m r^2$, for a hollow sphere $\frac{2}{3} m r^2$, and so on. Multiplying the moment of inertia by the angular velocity gives the angular momentum, otherwise called the moment of momentum, $m r^2 \omega$ or $m v r$.

An example is hardly helpful, but still we may reckon that a flywheel rim containing half a ton of matter, 12 feet in diameter, and revolving 20 times a second, has a moment of momentum $\frac{1}{2} \times 36 \times 40\pi$ ton-square-feet-per-second.

Sweeping of Areas

Now, this square-foot kind of unit is peculiar, and indicates that an area is being somehow swept out at a certain rate. The particle itself is not sweeping out any area; it is merely moving in a circle. No, but its spoke or radius is describing an area. It sweeps over the area of the circle at every revolution. And, as everyone knows, Kepler found that the law of speed of the planetary motions in astronomy could be expressed by saying that the radius vector of each planet (that is, the line joining it to the sun or force-centre of its orbit) sweeps out equal areas in equal times. The rate of describing areas is uniform.

Is there any relation between this geometrical rate of describing areas and the geometrical part of a revolving body's moment of momentum? Certainly there is. One is exactly half the other.

The area swept out by a spoke can be divided up into triangles, and the area of a triangle is the height multiplied by half the base. The height is r, and the base may be the arc described per second, namely, v; hence the triangle swept over each second by the carrying radius of a planet, or other body revolving in a circle, is $\frac{1}{2} v r$, while the moment of momentum is $m v r$. Disregarding the alien element of mass (alien, that is, to geometry) we see that the geometrical part of moment of momentum is exactly twice the rate of description of areas, and is the quantity commonly denoted in astronomy, or the dynamics of a particle, by h.

Every particle moving in a central orbit has its own rate of describing areas, no matter what the law of force may be. This law of equable description of areas holds exactly whenever the sole force acting is directed to a fixed centre. It is indeed another way of saying that the force acting and deflecting the body acts along the sweeping radius itself, which is pivoted at the far end on a definite fixed point. That point must be the centre of force: the law is not true for any other point. If there is any other kind of force—such as friction, for instance—which acts tangentially or otherwise than along the radius vector, the law of equable description of areas will not hold true. If the electrons, then, revolve inside an atom, and are attracted to the nucleus, they must describe areas uniformly; that is, they each have a constant moment of momentum characteristic of their particular orbit. But its value will be different for different orbits.

The electric case is simpler than the planetary, for the planets differ in mass as well as in size of orbit, whereas the electrons are all alike and differ only in distance from the centre of force. Every orbit will have its characteristic moment of momentum, and if we could say that this moment of momentum, having a certain value 1 for an innermost orbit, was 2 for the next, 3 for the next, and so on, it would be delightfully simple. In other words, if the moment of momentum, or, what is practically the same thing, the rate of sweeping areas, is not only constant for each orbit, but proceeds by equal steps or simple multiples from one orbit to the next, how much simpler the law of succession would be than the at present unknown law of succession of the planets—the discovery of which was attempted long ago by the astronomer Bode.

Bohr's Law

Well, strange to say, *this simple law does appear to hold, rather accurately, for the atomic orbits*. This was discovered not by Bode, but by Bohr. Calling the unit moment of momentum a *lot* (which is a convenient name employed by auctioneers for an indivisible group which you can either take or leave as a whole) the moments of momenta characteristic of successive orbits have to be 1 lot, 2 lots, 3 lots, etc., as the orbits increase in radii; and the result is that the radii of successive orbits proceed as the squares of the natural numbers, provided the law of attraction is as the inverse square of the distance—as for electrical attraction we know it is (see Chapter VII).

Kepler's Law plus Bohr's Law

It may be worth while to prove this last statement about the radii of successive orbits. Directly we find the inverse square law acting we can apply the well-known laws of astronomy, for instance the familiar laws of Kepler (see "Pioneers of Science" if necessary). Now according to Kepler's Third Law, r^3 varies as T^2 (cube of distance proportional to square of periodic time), or, what is the same thing, the product $r v^2$ is the same for all the orbits round a single attracting centre. Hence if $v r$ proceeds according to the natural numbers 1, 2, 3, 4, etc., in arithmetical progression, the radii r must proceed according to the squares of those numbers 1, 4, 9, 16, etc. This is algebraically necessary; as you may see by eliminating v. These are the successive Bohr orbits, with their radii as the square numbers; they seem to be the only stable and permanent ones; no other orbits seem possible. A particle may drop from one orbit to the next, but it cannot rest or revolve in any intermediate position. The full reason for this has still to be discovered, but the fact is evidenced by many considerations.

When revolving in one of the steady orbits, an electron somehow fails to disturb the ether; it emits nothing, and so retains its energy; but if it drop from one orbit to another is must emit surplus energy vigorously, in the form of radiation, either during the passage or as the result of the passage. This radiation is accordingly emitted in a discontinuous manner, or in jerks—one jerk or squirt of radiation for every drop—and the bright line spectrum—the familiar distribution of the luminosity—is thus accounted for.

CHAPTER IX

MAIN FEATURES OF THE RADIATION FROM THE SIMPLEST ATOM

Having ascertained or naturally assumed that the simplest atom is like an earth-moon system—with a central nucleus and a single planet or satellite revolving round it, attracted to the centre by an electric force varying as the inverse square of the distance, it becomes possible to apply well-known familiar mechanics to such a system, and to see how far the ordinary laws of mechanics would explain its behaviour as regards the emission of a bright line spectrum.

First, it is necessary to explain what empirical laws that spectrum was found to obey, before any attempt was made to explain them. That is to say, we must revert to the Kepler period, when the results of instrumental observation, which had accumulated during the Tycho Brahé period were analysed by Balmer and others.

The best-known lines in the hydrogen spectrum are those which were labelled C, F, and G, by Fraunhofer, who discovered them as black lines in the solar spectrum without in the least understanding their nature. C is in the red; F is in the greenish-blue; and G is in what Newton called the indigo part of the spectrum. That these three lines were due to hydrogen was discovered by Ångstrom in 1862, who found that he could get lines in exactly the same position by igniting terrestrial hydrogen. He found also other lines further up the spectrum, one of them far up in the violet. These lines seemed to constitute a series, the intervals between them gradually diminishing as one ascended the spectrum from red to violet. They each represented light of a definite wave length, or frequency of vibration; the word " frequency " meaning the number of vibrations executed per second in any particular kind of radiation, which must therefore correspond to some identical frequency of vibration in the source, that is to say, in this case, in the atom of hydrogen. (The frequency and the wave length are of course connected, so that their product is simply the speed of transmission—the velocity of light—as you may see by imagining all the waves emitted in a second put end to end.)

The law of this series was not discovered until after Sir William Huggins, by his wonderfully beautiful photographs of the spectra of stars, had detected about nine more lines high up in the ultra-violet or photographic part of the spectrum, also forming part of a regular series—though not the same series—and yet, like the lower one, having its lines getting closer together as you ascend the spectrum from the red or slower or bass end, towards the rapid or treble termination—if there be any termination—far beyond the violet.

Harmonics

In 1885, Balmer succeeded, after many trials and errors, in detecting the exact law of the main series. A series of ascending pitch or frequency of vibration obviously suggests what are called in music *harmonic* tones, which are most simply characterised by the natural numbers. When an open organ pipe is sounded, or when a piano string is struck, a trained ear can detect—or any ear if assisted by a resonator—not only the chief or fundamental tone, but a series of harmonics or over-tones; viz., the octave, the fifth above the octave, the double octave, the major third above that, the fifth above that again, and so on, the series of tones getting closer together as you ascend the scale; the law of their frequency being in that case quite simple, viz., in accordance with the natural numbers 1, 2, 3, 4, 5, etc. The first harmonic has double the frequency, or half the wave-length, of the fundamental; the second has three times the frequency, or one-third of the wave-length; the double octave has four times the frequency, or a quarter wave-length; and so on. They are called harmonics because they mostly harmonise in a pleasant manner with the fundamental tone, and enrich the note. A fundamental tone alone, without the harmonics, such as is given by a tuning-fork, is dull and uninteresting. A harmonic series is therefore valuable in Music.

So, naturally, when lines of a spectrum were found to constitute a series with decreasing intervals, many people had sought to detect harmonics of some fundamental atomic vibration, and they studied the wave-lengths or the frequencies shown by the carefully measured spectrum, in order to see if anything of the kind could be found. But the numbers did not fit; the series 1, 2, 3, 4 was not there. If the lines were harmonics, they were not the harmonics of open organ pipes or stringed instruments. But other series of harmonics are known. A closed or stopped organ pipe, for instance, will not give the whole series. It will give only alternate ones; its series of harmonics run 1, 3, 5, 7—according to the odd numbers, not the natural numbers. But neither would this series fit the hydrogen spectrum.

It was known, however, that other vibrating bodies, used in acoustics, less simple than strings and columns of air, could give harmonics of a more complicated kind—if, indeed, they ought still to be called harmonics, for they are not very harmonious. One, indeed, even of the simple harmonics of a string, is not harmonious, viz., that with seven times the vibrations of the fundamental; for this on the piano, in the key of C, would be represented by an upper B flat, and constitutes an obvious discord. To avoid this the hammers of a piano are arranged by the instrument-maker so as to strike the string at one-seventh of its length from the end, so as not to arouse this discordant seventh harmonic, which would require the struck point for a node or comparative place of rest.

So, also, the overtones of a metal disc can hardly rightly be called harmonics. If you strike a plate or a bar—or, for that matter, a gong—especially if you strike it out of the centre, or strike it with a fairly hard hammer, the clang produced is by no means harmonious; and when you come to analyse the series of overtones or so-called harmonics of a metal plate you find, not the natural numbers, but something closely connected with the squares of the natural numbers, 1, 4, 9, 16, etc. You find, indeed, no very simple law for the frequency of these over-tones, but a sufficiently simple one involving the squares of the natural numbers; such as this, for instance :—

$$\frac{n(n^2 - 1)}{\sqrt{(n^2 + 1)}}.$$

which, both theoretically and practically, will give the series of tones, if for n you put first 2, then 3, then 4, and so on. That is, the natural numbers do appear, but in rather a complicated fashion. This series of so-called harmonics is characteristic of a metallic clang; and, as is well known, complex notes of this kind can be used in music, like those of triangles, cymbals, drums and other noisy instruments, for producing special and striking effects.

Balmer's Law

It was natural, therefore, for Balmer to try whether the hydrogen atom might not perhaps be something like a plate or bell, so that its over-tones—which, in this case, are represented by the spectral lines—would involve the squares of the natural numbers. And, after many trials, he was successful in finding a comparatively simple and accurate law, viz., that the rapidity of vibration of the component lines in the hydrogen series could be represented by the expression :—

$$\frac{n^2 - 4}{4n^2}$$

where the n may be either 3, 4, 5, or 6. And this is now everywhere known as the famous Balmer Formula. It was the first introduction of simplicity, or an approach to law and order, among the complicated facts of spectrum analysis; and upon that fundamental, though simple, discovery a great structure has been erected.

The expression was purely empirical; no reason for it could at that time be given. It clearly belongs to the Keplerian, not to the Newtonian epoch. It was a most interesting discovery, though it did not quite correspond with the idea that an atom of hydrogen vibrated like a plate or bell. The law was somewhat similar, but different, and could not be accounted for by any system of mechanics at that time known. Balmer, however, felt the importance of his discovery, and expressed himself almost like Kepler, though with modern restraint, to the following effect :—

> The final impression which our mind involuntarily receives, in contemplating these fundamental relations, is that of a wonderful mechanism of nature the functions of which are performed with never-failing certainty, though the mind can follow them only with difficulty and with a humiliating sense of the incompleteness of its perception.

Reverting to the "search for harmonics" period, it is interesting to recall that that remarkable Irishman, Dr. Johnstone Stoney, found that the first, second, and fourth lines of hydrogen could be accurately represented by the frequencies 20, 27 and 32; which encouraged people in the search for some harmonic or numerical formula connecting all the lines of a series. The accuracy was more than could be attributed to accident. It can be verified that Balmer's Formula gives the same relative numerical ratio for three of the above special lines, the first, the second and the fourth. Writing these out with the lowest common denominator, viz., 3600, the relative frequencies become 500, 675, 756, 800; and dividing them all by 25 they become 20, 27, 30·24, 32. One of these is fractional, but the other three are exactly Johnstone Stoney's whole number ratios!

Much work was done also by Sir Arthur Schuster towards the detection of the hitherto undiscovered law of harmonic ratios; and his investigations were based on the splendid photometric measurements of wave-length by Liveing and Dewar; both of whom a short time ago were still well and active; and the elder of whom, the veteran Dr. Liveing, can still be seen at work in his laboratory at Cambridge; while Sir James Dewar died in the Royal Institution at the end of March, 1923.

Other Series akin to Balmer's

Since Balmer's time, innumerable other but similar series have been discovered, some in the visible part of the spectrum, some in the ultra-violet or high treble, some in the infra-red or deep bass part of the spectrum. And, though they cannot all be expressed in terms of Balmer's Law, they can be expressed in a very slight modification or generalisation of it, which is really easy to grasp, and which should be grasped if any progress is to be made in understanding what has been already done towards ascertaining the structure of the atom.

Just as a musician, even a blind musician, listening to an orchestra, can detect, from the multiplicity of the tones he hears, by means of the marvellous analysing mechanism of a musical ear, which instrument is producing each note, and can form a mental picture of what the performers are doing; so an observer with a modern spectroscope—or, rather, one who scrutinises with metrical and punctilious care the photographs obtained by such an instrument—can now realise the kind of structure which is emitting the various rays, and can even—as we shall see—begin to form a mental picture of the way in which different atoms are behaving; can even see, as it were, the movements of the performers with the mind's eye.

This may seem a rather marvellous feat for a blind musician; and so, no doubt, it is; but it represents, as in a parable, our own work in interpreting the lines of a spectrum, and in a general way its possibility can be understood. Even an untrained ear can tell the difference between a stringed and a wind instrument, or between different kinds of wind instruments, the metal and the wood. A clarionet and a cornet may be sounding the same fundamental tone, and so may a harp and an organ, but the quality of the sound is different in each case; and no one could mistake the one for the other.

This last elementary kind of rough discrimination represents all that we were able to do in the early days of spectrum analysis. Anyone could tell that certain of the main lines were due to hydrogen; that the yellow line was due to sodium; that certain lines in the solar spectrum indicated iron; and, indeed, that the presence of chemical substances could be detected by examining either their emission or absorption spectra—that is, by measuring precisely the kind of light which they gave out or took in. Now, however, owing to recent discoveries, we have got far beyond all that; and, as compared with our scientific ancestors—not through any merit of ours, but through the progress of discovery—we, or those who are working at this subject, are in the position of a trained and skilled musician, as compared with a yokel who can barely tell one tune from another.

Empirical Law of Spectral Series

The modification which has to be introduced into Balmer's Formula, to generalise it and make it represent other series, was introduced by Ritz, who made *two* of the symbols proceed by natural numbers, instead of only

FIG. 1 —A PHOTOGRAPH OF THE IONISATION BY AN X-RAY BEAM, SHOWING PATHS OF ELECTRONS LIBERATED FROM ATOMS OF GASEOUS MATTER.

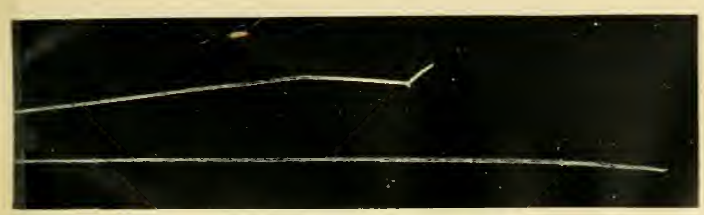

FIG. 2 —ALPHA RAYS FROM RADIUM. A PHOTOGRAPH OF THE PATH OF AN ALPHA PARTICLE EJECTED FROM THE NUCLEUS OF A RADIUM ATOM.

FIG. 3.—A PHOTOGRAPH OF THE PATHS TAKEN BY SEPARATED IONS.

(*Photographs by courtesy of Cambridge Instrument Co., Ltd.*)

one, in a way we shall deal with a few paragraphs further on.

The Balmer expression may be written, by merely an algebraic change, in the equivalent form :—

$$\frac{1}{4} - \frac{1}{n^2}$$

where, as before, the n is to proceed discontinuously like the natural numbers, and where each value of n thus introduced into the formula is to give a line in the spectrum, or what we have likened to an over-tone or harmonic.

On looking at this expression you see at once that n cannot be less than 2, or the whole thing would become negative and meaningless. Next you see that if n is equal to 2, the expression is zero. Hence, the smallest value of n which is any use is 3. There is no limit to the largest value. Successive lines are given by putting $n = 3, 4, 5, 6$, etc. The frequencies thus calculated run thus :— $\frac{5}{36}, \frac{3}{16}, \frac{21}{100}, \frac{2}{9}$, etc.; a series which, as n increases, rapidly converges on to the ultimate limiting value $\frac{1}{4}$. This series accurately agrees with actual spectrum measurements, to a surprising degree of exactness.

Now what about the first term in the Balmer expression as just above written? As it stands, the denominator represents the square of 2. Why not the square of 1, or of 3, or of something else? The only question is: Will such a change give any result in accordance with observation? On putting this to the test it was found that this Ritz or modified Balmer Formula could give, not the one series only, but a number of series, some of which had been observed, and some which had not been observed; some in the ultra-violet, some in the infra-red. So these were looked for, and in due time found. The main law of all the series of spectral lines had been discovered!

Anticipation of further Consequences

The discovery, however, was still empirical; and minute discrepancies might be noticed by very accurate observation. That is exactly what happened also with Kepler's Laws; they are not precisely accurate. They are a first and very close approximation; and they only give proportionality; they do not give equality. Kepler's Third Law, for instance, which says that the square of the periodic time is proportional to the cube of the greatest diameter of the orbit—or what is roughly called the cube of the distance—was entirely empirical; and no attempt was then made to specify the nature of the constant ratio between T^2 and a^3. That was reserved for Newton. He showed that this constant ratio was characteristic, not of a planet—since it was the same for all the planets—but of the central sun. By it he was able to determine the mass of the sun; or, in popular words, to weigh it. So also, by means of the satellites of Jupiter, it became possible to weigh Jupiter; and, by the satellite of the earth, to weigh the earth, relatively to other astronomical bodies; and indeed it was possible to weigh all of them absolutely, provided only that we knew a certain gravitation-constant—how much a pound of matter attracted another pound a foot away from it—a very small value which was ascertainable by refined laboratory experiments.

Is it possible, then, from the modified Balmer Law to find out something about that central atomic nucleus which corresponds with the sun in the astronomical problem? That is a question which at once suggested itself: and it was brilliantly answered by Bohr. The answer is: Yes. The attracting force of the central nucleus can be calculated, the empirical formula can be rationalised. It can be made to give, not relative frequencies only, but absolute. That part of the mechanism can be understood. It was this great discovery which forced the astronomical or orbital theory of the atom upon the attention of physicists, and began, or at least heralded, the beginning of a Newtonian period! But we must hold this over until we have entered into details about the lines in a spectrum rather more closely.

CHAPTER X

THE ARITHMETICAL TREATMENT OF LINE SPECTRA

The Balmer Formula is worthy of close study, and the lines given by it should be plotted on some convenient scale. Writing it, as subsequently developed, in the form

$$B\left(\frac{1}{n_1{}^2} - \frac{1}{n_2{}^2}\right),$$

we see that we have two integer numbers at our disposal, n_1 and n_2. So long as they are integers, the expression will give a line in a spectrum. If we change n_2 only, we shall get the lines of a single series. And if we change n_1 we shall proceed from series to series. This will become clearer directly, for the lines given by that sort of arithmetic can be plotted, and it will be found that they agree precisely with spectrum lines when reduced to a certain scale. The scale depends on the at present arbitrary constant B (called Balmer's constant, or often called Rydberg's constant), and the absolute evaluation of this constant is what we have hinted at enthusiastically at the end of the last section. But in this exposition we are not supposed to know anything absolute yet : nor is it necessary at present. For plotting purposes we can take for B any convenient value; and then, fixing a value for n_1, we can get a single series by making n_2 proceed as the natural numbers. To get another series we can do the same thing, but must choose first a different value for n_1.

Let us take for B any convenient number, such as 3600, and keep $n_1 = 2$, so as to get the Balmer series proper, as n_2 increases through 3, 4, 5, 6, etc. To get another series we might take $n_1 = 3$, and then make n_2 take the successive values 4, 5, 6, etc. We thus get a similar series, which is really a part of the same group of lines, but shifted lower down the spectrum. To get a higher series we can take $n_1 = 1$, and then we get again the same group, but higher up, and with an extra initial term. To make this clear, we can plot the several series one below the other, beginning with $n_1 = 1$.

Each series has a head or terminus, beyond which it does not go, and in which the upper lines of the series are crowded together, always approaching the head, but never quite reaching it. The head of each series is given by $1/n^2$; so that the heads of successive series, beginning with $n_1 = 1$, are :—

$$1, \ \frac{1}{4}, \ \frac{1}{9}, \ \frac{1}{16}, \ \text{etc.}$$

The original Balmer series is the second of these, and, for hydrogen, is in the visible part of the spectrum. The first series, even for hydrogen, is far up in the ultra-violet, while the third is in the infra-red. For heavier elements all the series shift up into the violet, and away towards the region of *X*-rays. But that statement is premature; we are dealing at present only with relative positions, as given by integers in the discontinuous or "counting" kind of arithmetic.

Plotting of the different Series of Lines

To make all this clearer let us plot the lines, from the formula for their frequency or reciprocal of wave-length, choosing any convenient value for *B*, say 3600,—

$$3600\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

The first series will have $n_1 = 1$, with n_2 successively 2, 3, 4, 5, 6 . . . ., giving the numbers, 2700, 3200, 3375, 3456, 3500, ... 3600. The head of the series, up to which an infinite number of lines crowd, though they may be of insignificant intensity or physically non-existent, is given by the number 3600. No line of the series can occur above that position, and no line of that series will be found below the number 2700.

The second series will have $n_1 = 2$, with n_2 successively 3, 4, 5, 6 . . . ., giving the numbers, 500, 675, 756, 800, ... 900.

The head of this second series is 900; and between the limits 500 and 900, the whole series is found.

Looking at the relative size of the numbers we see that these two series are a long way apart, *i. e.*, are in a quite different part of the spectrum; but if we compare the intervals between the lines we shall find that all but one of the intervals correspond. In the portions above recorded the following intervals occur in both series :—

175, 81, 44,

while the first interval of the first series, namely, 500, is the fundamental of the second series. This sort of thing is general throughout.

The third series will have $n_1 = 3$, and n_2 successively 4, 5, 6, etc.; giving the numbers :—

175, 256, 300, ... 400;

so that the intervals of this series are :—

81, 44, etc.;

while the fundamental of the third series is the first interval of the second.

The fourth series has $n_1 = 4$, and $n_2 = 5$, 6, etc., giving :—

81, 125, ... 225;

where again we shall see that the same law holds.

The fifth series $n_1 = 5$ has as its fundamental 44 . . . . and its head at 144, and so on. The plotting follows. And it will be seen that to change from any one series to the one below it, we have only to shift the whole set, as if on a movable slip, one step to the left.

Method of Tabulation

We first tabulate the first few lines of each series, reckoning from zero on any convenient plotting scale. But the first step is so big that 500 has had to be subtracted from all its numbers to bring it on to the paper. The other lines are then plotted in the right positions. The intervals begin by being roughly about halved each time as you go up, but they shade off into equality as n gets big. The ratio between any one interval and the one which follows is

$$\frac{2n+1}{2n-1}\left(\frac{n-1}{n+1}\right)^2$$

The head of each series is the same distance from the corresponding line of each series.

TABULATION OF THE BEGINNING AND MAIN PART OF SOME OF THE SERIES OF SPECTRAL LINES

	First Series $n_1 = 1$.	Second Series $n_1 = 2$.	Third Series $n_1 = 3$.	Fourth Series $n_1 = 4$.	Fifth Series $n_1 = 5$.
$n_2 = 1$	0				
$n_2 = 2$	540	0			
$n_2 = 3$	640	100	0		
$n_2 = 4$	675	135	35	0	
$n_2 = 5$	691·2	151·2	51·2	16·2	0
$n_2 = 6$	700	160	60	25	8·8
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
$n_2 = \infty$	720	180	80	45	28·8

These series have immense importance in the Bohr theory of the atom; that is why they are worthy of study. They will be found to correspond each with a special orbit in the atom; and these orbits are conventionally labelled K, L, M, etc., to correspond with observed series of spectrum lines which had been denoted by the same letter. What we have called the first series is labelled K, the second is called L, the third M, and so on. It should be noticed that the intervals between lines in the various series show a strong family likeness; in fact identity, except that they occur in different absolute positions, and except that an earlier series has one fundamental line on the left more than the next later one has. Thus the K series only has the line we have labelled A. The series K and L both have the line marked B. Three series, K, L, and M, have the line C; and so on. (See also p. 148.)

Typical Series of Line Spectra.

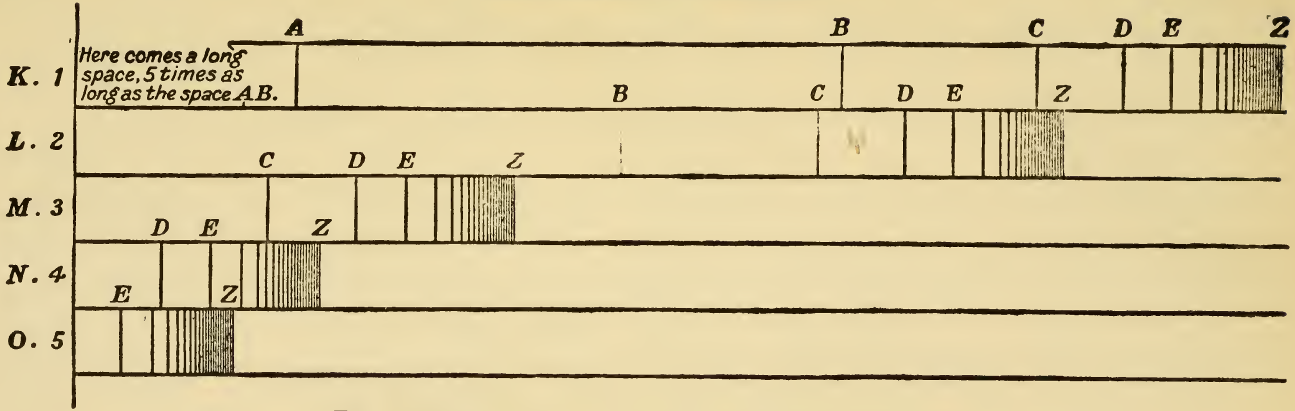

Fig. 7.—Plotting of the Main Type of Spectrum Series.

Corresponding lines of each series are similarly labelled. The interval *C D*, for instance, is the same in all. The head of each series is labelled *Z*; it must be understood as a fade-away and mere boundary, not a genuine line. In so far as the portion *E Z* is represented differently in the different series, it is mere error in drawing the crowd of lines.

In hydrogen the second or L series is mainly in the visible part of the spectrum. The first, or K series, is far up in the ultra-violet; the third, or M series, and all the others, are in the infra-red.

The labelling is not Fraunhofer's labelling. The lines B, C, D, in the second spectrum he labelled as C, F, G. They are three of the familiar old Fraunhofer lines in the Solar Spectrum, and have long been known as indicative of hydrogen in the sun.

CHAPTER XI

RELATION OF SPECTRUM FACTS TO POSSIBLE ORBITS

Before leaving the subject of line spectra, pure and simple, we may notice a few more considerations about their formula, the importance of which is emphasised by the fact that the relative values reckoned by this formula agree, to an extraordinary degree of accuracy, with the carefully measured position of the lines in the spectrum. Indeed, the expression so far given, as soon as the constant B had been theoretically evaluated by Bohr on a kind of astronomical basis, gave their absolute position too, and enabled the details of fresh series of lines to be predicted;—lines which had never been seen, since they are in outer regions of the spectrum, above and below the limits of vision. These lines were afterwards discovered and their position measured; and they were found to be precisely in accordance with the laws laid down for them.

Referring once more to the numerical part of the formula for the frequency of vibration in the radiation emitted by atoms,

$$\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right),$$

the integer n_1 fixes the number of the series, while $n_2 - n_1$ fixes the number of each line in the series. If we interpret these integer numbers as representing numbered orbits, as we shall hereafter, the suggestion of the above expression is that it represents a drop of a particle, such as a revolving electron, from orbit n_2 to orbit n_1, and that the frequency of the emitted radiation depends on this drop. Each orbit will have a rate of revolution characteristic of the orbit, and, as in astronomy, particles in the smaller or inner orbits will have a quick rate of travel, or a short year, while those in outer orbits will have slower motion and a long 'year' or period of revolution.

If we take n large, we get a slow rate of vibration, or comparatively long-wave radiation, which, if emitted by a particle revolving in or dropping into an orbit, should correspond to an outer orbit in which the speed is correspondingly slow and the time period correspondingly long. For some large value of n the orbit will be the biggest allowable, and the first line of that spectrum, due to a drop from that orbit to the next, will be the slowest on record. Its frequency, or inverse wave-length, will be given by the expression

$$\frac{1}{(n-1)^2} - \frac{1}{n^2},$$

which may be written by simple algebra as

$$\frac{2n-1}{n^2(n-1)^2},$$

or, when n is very large, $2/n^3$.

This is a curious and (as it turned out) suggestive value for the frequency, viz. that in an extreme case a particle can emit radiation of a frequency inversely as the cube of the number of its orbit; and accordingly a few more words may be advisable on this point. The above algebraic expression, when n is fairly large, approaches the value $2/n^3$, though it is always a little bigger than $2/n^3$. Let $n = 10$, for instance, then the value of the true expression is 0·0023456 . . . whereas $2/n^3 = 0{\cdot}002$; so even with $n = 10$ they are not very different. If n were 100 the two values would approximate much more closely, within $1\frac{1}{2}$ per cent. The difference between them in general is

$$\frac{3n-2}{n^3(n-1)^2}$$

and thus gets rapidly smaller as n increases.

Another mode of statement is the well-known algebraic or mathematical fact that

$$-\frac{d}{dn}\cdot\frac{1}{n^2} = \frac{2}{n^3},$$

whenever the decrease of n is small compared with n itself; the decrease of n being, in our case, unity, and not a real differential at all. Differentials, in fact, are out of place in quantum theory. All steps are finite ones. The step we have just reckoned is the smallest step possible in atomic spectrum theory, and gives the lowest frequency of vibration. When a particle in the atom takes this step it emits the smallest possible amount of energy under the circumstances; as we shall see.

Attempt to Reconstruct the Steps by which Bohr arrived at his Theory

It is not easy to follow the workings of a mind of genius; but it is likely that the clear fact that has now emerged, viz. that the frequencies of vibration of successive lines in the spectrum are represented by the difference of the reciprocals of the squares of the natural numbers, combined with a law of gravitational orbits well known to astronomers—that the energy of a planet is proportional to the reciprocal of the radius of its orbit—suggested to Professor Bohr that the two apparently diverse facts might be unified by postulating that there were several possible orbits, and that their radii proceeded as the squares of the natural numbers; for then the spectrum radiation frequency would depend on the difference of reciprocals of orbital radii, which is an energy expression. And thus there would be a close connection between energy and frequency; since both could be expressed in the same sort of way.

A relation between energy and frequency had been forced upon the notice of Professor Planck in the last month of last century, and formed the basis of his Quantum Theory. Later Professor Einstein laid down his famous confirmatory though still empirical proposition, that in order to regularise and reduce to order a large collection of facts, it was necessary to assume that the energy sent out by a radiating body was emitted in packets, and that the size of the packets was proportional to the frequency or inverse wave-length of the radiation. So that $\frac{\text{energy}}{\text{frequency}}$ = a constant, or an integer multiple of a constant.

We now find—or rather Bohr did, in or about 1913—that the postulated procession of orbital radii as the squares of the natural numbers, when considered astronomically, requires that the rate of sweeping areas, or the moment of momentum of an electron revolving inside an atom, is an atomic sort of quantity that proceeds by "lots" or indivisible steps from one orbit to the next, and that energy is only emitted when a particle jumps from orbit to orbit. For if r proceeds as n^2, Kepler's Third Law shows that vr will proceed as n. (See Chap. XIX, and p. 152.) This is expressible by saying that the moment of momentum is an integer multiple of some atomic unit which for the present we will call A; so that

$$mvr = mr^2\omega = nA.$$

To convert moment of momentum (mvr or $mr^2\omega$) into energy we must divide it by a time, or, what is the same thing, multiply it by a frequency, that is a number per second.

So we can write a simple expression for twice the kinetic energy of the revolving particle as

$$mv^2 = mr^2\omega^2 = nA\omega.$$

Moreover, if r proceeds as n^2, Kepler's Third Law shows that the time period of revolution proceeds as n^3. Remember, we found just now that the frequency of emitted radiation in certain cases proceeded as $2/n^3$; so there is evidently some connection between orbital frequency and radiation frequency. What we have written as $nA\omega$ Planck had already written as proportional to $nh\nu$, where ν is radiation frequency. It is tempting to write $\omega = 2\pi\nu$ and $A = h/2\pi$; but we must be careful: see pp. 122, 135, 163, 175.

We may anticipate an elementary exposition in Chapter XII by saying that dynamically the above double of the revolving energy is really the whole energy of the particle, if it is moving under the action of a central force varying inversely with the square of the distance; that is to say, it is the energy which it could have acquired by falling into its position from infinity, or the energy which could extract it from rest at that place and fling it away. In the case of a circular orbit half the total energy is accounted for as kinetic; and an actual revolving particle, having already the half value in virtue of its motion, needs only the other half to be supplied in order to enable it to escape. If, instead of escaping, it only goes into some outer orbit the total energy required will be a simple difference.

This emergence, or ladder-climbing, of a particle would require a supply of energy from outside, to be absorbed by the particle; which might be supplied by radiation of the right sort. And conversely, if the particle drops from an outer to an inner orbit, it should emit energy. True, it will be moving more quickly in the inner orbit and therefore will have more kinetic energy there, but it will have acquired in its fall twice as much, and so it has a balance to emit as radiation, of a frequency to be determined if we can.

It is natural to think that the frequency of radiation must somehow represent or depend on the number of revolutions per second; and there are grounds for thinking that that does correspond to the lowest of the lines which a particle can emit; as was hinted near the beginning of this chapter. But this is a matter to which we must return, for it is not easy to connect revolution with vibration frequency; since at least two orbits are involved in the latter. The particle drops from one orbit, and into another: which frequency are we to take? We will leave this for the present, and now proceed to some elementary mechanical or dynamical propositions about revolving particles in general.

CHAPTER XII

ENERGY CONSIDERATIONS IN ORDINARY INVERSE SQUARE ORBITS

As a preparation for the understanding of the conditions of electrons revolving round an electrically attracting nucleus, it may be best to begin with the more familiar example of ordinary gravitation, that is, of a particle or a satellite attracted by a body like the earth, and describing an orbit round that body if the particle is travelling free and unimpeded. It is known from Kepler's Laws that every such particle must describe an ellipse with the centre of the earth as one focus. A cannon shot or even a cricket ball describes a portion of such an ellipse. It is unable to describe more, because the bulk of the earth intervenes; the earth is a target difficult to miss, and therefore the motion soon comes to an end. But if all obstruction were removed, and if the earth can be imagined reduced to an attracting point at the centre, then the cricket ball would continually revolve round the central point 4,000 miles away, in an elongated ellipse, returning to its starting point after the lapse of a calculable time, which, as a matter of fact, would be just less than half an hour.*

We only see the upper portion of this orbit; and it is commonly called a parabola, because the centre of attraction is so far away. It is not a true parabola, even in a vacuum, but it is an ellipse so elongated that for all practical purposes any portion of one end of it would coincide with a parabola.

If a projectile could be fired horizontally with a sufficient speed, and if the obstruction of the earth's atmosphere were removed (which could only be done by ascending to sufficient height above it), then the projectile might circulate right round the earth and come back to its starting point

* For $T = 2\pi\sqrt{\frac{a^3}{\mu}}$; where $a = \frac{1}{2}R$; $\mu = \gamma M = gR^2$.

So $T = \pi\sqrt{\frac{R}{2g}} = \sqrt{\frac{10^9\pi}{981}} = 1790$ seconds.

periodically; the time taken in this journey being under two hours. The speed necessary for this circular revolution would be about five miles a second. If shot with any velocity less than this it would hit the earth sooner or later; and if fired with a velocity greater than this—say six miles a second—it would describe an elongated ellipse enclosing the earth, but passing above the Antipodes far overhead. If fired at seven miles a second that ellipse would be infinitely elongated. It would become a parabola, and the projectile would never return. It would travel away to infinity if there were no other body in the universe; but actually it would get inveigled by the attractive power of the sun, to overcome which a speed of twenty-six miles a second is necessary, and thereafter circulate like a small comet captured by the earth. That, however, is by the way. The important thing for our present purpose is to consider the energy of motion of a body revolving in a circular orbit round the earth at any given distance from its centre, and what relation it bears to the energy acquired by a body falling to the earth from a great—that is, practically from an infinite—distance. The one energy turns out to be exactly twice the other; as can be proved thus. We have only to equate the weight of the body—that is, the attraction which the earth exerts upon it—to the centrifugal force; or—more accurately expressed—we have to state that the centripetal force needed to curve the path of the body into the form of a circle, is simply its weight. Or, in other words, we have to express that the weight of the revolving body is the sole governing force acting.

Now the weight of a body near the earth is commonly written mg, and the centrifugal force of a body revolving near the earth is mv^2/R, where R is the radius of the earth; v being, of course, the speed of the body. So writing down that these two quantities are equal we get at once

$$v = \sqrt{(gR)}.$$

And if this be interpreted numerically we find that it is just about five miles a second. For it is the square root of the product of 32 feet per second per second and a length of 4,000 miles, the evaluation of which is a mere matter of arithmetic, the answer coming out in either feet per second or miles per second, just as you like.

If we now perform another little calculation for a body falling from an infinite distance under the inverse square law, we shall find that, given no obstruction, the speed with which it will reach the earth is $\sqrt{(2gR)}$. And that same speed would enable a projectile just to get away to infinity and so escape from the earth. This speed you see is $\sqrt{2}$ times the speed necessary for rotation. Hence, if one is five miles a second the other will be about seven miles a second, since $\sqrt{2}$ is 1·4 approximately.

Now kinetic energy, as everyone knows, is proportional to the square of speed, and is commonly written $\frac{1}{2}mv^2$. Hence the energy acquired by a body falling from infinity on to the earth is mgR. And the energy a body must possess in order to enable it to revolve round the earth is $\frac{1}{2}mgR$. Or as it is sometimes expressed, it is the energy which would be acquired by a free fall under uniform gravity through a height equal to half the radius of the earth. Whereas the energy from infinity, or what may be called the escape energy, is equal to the free fall under uniform gravity through a height equal to the whole radius.

These expressions are general, and apply, if properly interpreted, to any particle at any distance away from the earth; provided the right value of g is used, as well as the right value of what would now be called r. Thus, suppose we were at the distance of the moon from the earth. That distance is equal to sixty times the earth's radius. Hence the force of gravity would be diluted down to $\frac{1}{3600}$th of its value at the surface of the earth, since it varies inversely with the square of the distance. So, expressing this value of g by g' at the distance r, the speed of the moon in its orbit must be $\sqrt{(g'r)}$, and the speed with which the moon could escape from the earth would be $\sqrt{(2g'r)}$; which two speeds, interpreted in figures, would be $\frac{5}{\sqrt{(60)}}$th of a mile per second, and $\frac{7}{\sqrt{(60)}}$th of a mile per second, respectively.

The chief thing we have to notice, is that the energy needed for escape is just double the energy required for circular revolution, in every case. Or in other words, that if the revolution energy of any planet were doubled —by the addition of an equal amount of energy to that which it already has—the planet would escape from control and fly away. But now that we have to do with a variable g—since in our imagination we are no longer limited to the surface of the earth, as we are in our bodily condition—it is best to dispense with g and replace it by the more fundamental Newtonian expression

$$\frac{\gamma M}{r^2};$$

for the intensity of terrestrial gravity at any point in space. For, of course, the attraction is due to the mass of the earth, which is here represented by M; and γ is the Newtonian gravitation constant representing the attraction of two unit masses at unit distance, an important physical constant which has to be determined by direct experiment —an experiment which was first performed by that great philosopher, Cavendish, more than a century ago, and which in our times has been repeated with extreme precision by Mr. Vernon Boys. It is not necessary for our present purpose to trouble about the value of this constant, and for illustrative purposes it may be best to omit it, and to consider that the mass of the earth is measured in what are called gravitational units—whatever they may be—for they have the effect of reducing the gravitational constant to unity. So that we may say that the value of g near the surface of the earth is M/R^2; and that, at the distance of the moon, the corresponding value is

$$g' = \frac{M}{r^2}; \text{ where } r = 60R.$$

Substituting these values in the velocity expressions, we get for the revolving speed (at any distance r)

$$v = \sqrt{\frac{M}{r}};$$

so that for the kinetic energy ($\frac{1}{2}mv^2$) of, say, the moon, whose mass is m, we get the simple expression

$$\frac{mM}{2r};$$

and for the escape energy at the same place twice this value, viz. mM/r. Or, since $M = 80m$ approximately, we might call this total or sort of negative energy

$$-\frac{80m^2}{r}.$$

Negative, because it must be supplied to a stationary body before it could escape altogether. The moon does not really possess it; if it did, it would escape. It only possesses half of it: and that carries it round in a circle. This is a simple law which holds universally and which may be adopted as here proven, even by those who do not care to follow what are really the very simple steps of the proof.

Summary

I will state the law in general terms. Any particle revolving in a circular orbit about a centre of force attracting as the inverse square of the distance will require to have imparted to it an amount of energy equal to that which it already possesses, before it can escape. And, further, this energy is proportional to the effective attracting quantity in the centre of force and inversely as its distance away. In the gravitational case the mere bulk of any considerable mass of matter causes the distance of its centre to be necessarily great, and therefore the energy of all revolving satellites to be moderate. But when we come to the electrical case, the centre of force is exceedingly concentrated, the intrinsic forces are very great, and the distances may be exceedingly small; consequently the speeds of revolution are excessive and the energy of revolving or escaping particles enormous.

Otherwise the gravitational and electrical cases would appear to be alike, unless the excessively small distances introduce some unexpected element like the quantum; and we should *expect* to be able to say in both cases, as we certainly are in the gravitational one, that if you give a revolving particle any additional energy, of amount less than what it already possesses for circular motion, it will be perturbed and will no longer describe a circular orbit, but will describe an elliptical one. It will describe an ellipse whether you increase its energy or decrease it, provided the increase or decrease is less than a critical value. If you take away all the energy that it possesses, it will simply drop on to the attracting body. If you add to it as much energy as it already possesses, it will fly away in a parabolic orbit to infinity. Otherwise it merely changes its orbit, continuously in the gravitational case, discontinuously in the electrical case; for an electron surprisingly abandons one orbit and accepts another when a suitable quantum of energy is withdrawn or supplied.

All this applies, in the main, to the condition of an electron revolving round a nucleus in an atom. But whereas in the gravitational case the addition and removal of energy is beyond our power, it is not at all beyond our power in the atomic case. As so often happens, we find that we have more control over electricity than we have over matter. Electrons revolving in circular orbits do escape; and also sometimes they fall in, from what, compared with the atom, is an infinite distance. Hence considerations which astronomically are hypothetical, though instructive, become in the atomic case actual practical considerations, such as we constantly encounter in the laboratory.

The attraction in the atomic case is, of course, not gravitational, but electrical. The nucleus is charged with the positive quantity E, and the electron is charged with the negative quantity e; so that, at any distance r, the force of attraction, which is no way proportional to their masses, is

$$\frac{Ee}{r^2}.$$

This replaces the gravitational Mm/r^2; ignoring the ether-constant in both cases. And this is what constitutes the centripetal force

$$\frac{mv^2}{r}.$$

Hence the energy of revolution of the electron, given by equating the two last expressions, is

$$\tfrac{1}{2}mv^2 = \frac{Ee}{2r}.$$

And the additional energy that must be given to it to enable it to escape is also

$$\frac{Ee}{2r},$$

the energy of escape being the sum of the two, or

$$\frac{Ee}{r}.$$

This is a very simple law, and it applies to every electron in an atom, no matter at what distance it is from the nucleus, so long as it is either escaping, or coming in, or revolving in a circle. If it is revolving in an ellipse a little geometry has to be introduced, of a simple character, but still not quite so simple as that of the circle.

CHAPTER XIII

INVERSE SQUARE ORBITS SUBJECT TO THE QUANTUM KIND OF DISCONTINUITY

LET there be a number of possible orbits, or a number of actual revolving electrons, distributed round the centre in the same general sort of way as the planets in the solar system are distributed round the sun. And let us say that the radii of the orbits run as the squares of the natural numbers, that is to say, 1, 4, 9, 16, 25, starting from the centre as zero. And for simplicity let all the planets be of the same mass—in fact, let them be like electrons. We have further to suppose that no other orbits are possible —which is an odd assumption not justified by dynamics, and peculiar to the quantum. These peculiarities were suggested, as we have already seen, for the case of atoms, by the spectrum which they are liable to emit.

So now let us consider what must happen to the energy if an electron is to be dropped from some outer orbit into some inner one. If we could take all its kinetic energy from it suddenly, it will drop into the centre. But if we take a portion of energy from it, or if, by reason of some collision or disturbance, it loses a portion of its own energy, so as to slacken speed, it would work down either gradually or suddenly nearer to the centre, and must apparently be supposed to reach an inner orbit, where it can revolve peaceably, like the electron that is or might be already at home there. We must not suppose that in this inner orbit it has less kinetic energy than it had in the outer one, for that would be contrary to fact; the inner planets are moving more quickly, and so have more kinetic energy, than the outer ones. The electron has gained energy in the fall. It gains by the fall twice as much as is needed to allow it to revolve in the inner circle. If we call any inner circle number 1, and any outer circle number 2, its energy in the outer circle was

$$\frac{Ee}{2r_2}.$$

Its energy in the inner circle is

$$\frac{Ee}{2r_1},$$

which is greater. But in the fall it has acquired twice this difference. It gains in the fall twice the energy which it need retain. It has gained by taking up its new position, and has a surplus to emit. And so every time it drops from one orbit to another, it has to give up a certain amount, and it acquires, by falling, not only that, but also so much more as will enable it to circulate in the new and more energetic inner circle. Hence the amount of energy which has to be got rid of in order to allow it to settle down from an outer to an inner circle, is exactly equal to the difference of the energies in these two circles.

Further Exposition about Energy

There is something peculiar about the energy gained by a falling body, especially when applied to the case of these curious intermediate stages or possible orbits. Such orbits do not occur in ordinary dynamics; and so it is quite possible to get confused about the specification of energy, especially with regard to sign.

Ordinarily, a falling body loses potential energy and gains kinetic. Work is done by gravitation upon it as it falls; and this amount of work must be done, by something, if it is to be raised again to the height whence it came. Its own kinetic energy would (in the ordinary case) suffice to carry it back, if its motion were reversed in direction. But then an ordinary falling body is not radiating anything. It is not losing any energy, except in a resisting medium. Nor does it encounter a series of possible orbits at right angles to its line of drop. If it did—and I suppose we can imagine such a thing—we might have a particle falling say towards the earth and at a certain stage meeting a check, like a smooth circular path provided for it, the check making it give up half its energy and circulate with the remaining half. If it had dropped a long way before meeting with this check, it would have acquired a great deal of energy. It would have a great deal to give up, and it would circulate very rapidly in its path. But its retained or circulating energy would be quite insufficient to raise it back again: it is just enough to enable it to revolve in its new position: the lost half energy must be restored to it before it is to be able to return.

Let us repeat. Our electron, falling in towards the centre under electrical attraction, loses potential energy and gains kinetic; and the kinetic so gained is double what is needed for circular revolution. Hence if for some unknown reason it does stay and revolve in a circular orbit at any given position (which it ought not to do on purely Newtonian principles), it must get rid of or radiate the other half. And to drive it back again, this lost energy must be restored. So its energy of position has a negative quality. The particle really had more potential energy when at a great distance. And if we attribute greater total energy to it as it drops, because of the work that has been done upon it, it is convenient to attach to that total energy a negative sign; for it represents the total energy needed to remove it and throw it back. Its kinetic energy it really possesses; and the amount of that increases as it approaches the centre. But its potential energy it does not possess. And near the centre it has only a residue, in amount Ee/r. It looks big, because r is small; but considered as energy, it is negative. Considered positively, it is the work done during the drop. And of the result of that, half has been emitted and half retained. It is getting near the bottom. It has no power of raising itself. The energy, therefore, considered as potential, is not really a possession but a debt; a summing-up of what has been, rather than of what is. It is not Ee/r but $-Ee/r$.

The greater its numerical amount, the less of that kind of energy does the body possess of its own, and the more work must be done to raise it.

The negative sign attached to the potential energy of a falling body is orthodox and natural enough. But then it is usually accounted for by the positive and actual gain of kinetic energy. The intra-atomic case is complicated by the fact that only half the work done is accounted for by the kinetic energy possessed. The other half, at certain stages and with apparent suddenness, goes away in radiation of a definite frequency, depending on where it has come from and where it has got to. It is hopeless, at present, to attempt to give a clear dynamical exposition of this curious behaviour; though no doubt as knowledge increases we shall be able to explain it somehow. For the present we must just accept the fact; just as we have long been accustomed to accept the fact of a falling body, without clearly understanding what it is that makes it fall.

Rough Illustrative Model

Can we make any simple mechanical model illustrative of this discontinuous kind of drop, or dropping by steps? Think of a marble rolling down a staircase. The analogy is not very close, but let us see if it serves at all. At the top it has a certain amount of energy, depending on the motion with which it is rolling towards the edge, and on its height above the ground. When it comes to the edge it tumbles over and acquires speed in its descent, so that it is moving more rapidly than before; but the blow, when it strikes, makes a noise and, therefore, gets rid of some of the energy. It then goes on dropping from step to step, losing a little every time but gaining more than it loses, until it arrives at the bottom.

If the staircase were made circular, like a conical pyramid cut into steps, and if the marble was running round the steps in a sort of spiral, and if the risers between the steps increased in depth from the top downwards, and if it could bounce over some of the steps, then we should have a very rough and unsatisfactory model of our orbits with a particle travelling continually downwards, losing potential energy as it went, but gaining kinetic energy. A rough and unsatisfactory model, but one which does suggest a discontinuous kind of fall, and also the emission of radiant energy in the form of sound or vibration every time there is an impact; the impacts getting more and more violent as it approaches the bottom.

To make the rough analogy less incomplete we *might* picture to ourselves a number of marbles on the conical staircase, one on each step, and each revolving round in fairly stable condition due to a slight groove or depression round the step; and then we might picture another marble thrown in on the top, which would precipitate the first over the edge and take its place. That one would precipitate the second; and so on to the bottom, like the bricks set up on end called "sending Jack for mustard." And we *might* think of all these catastrophes as occurring nearly simultaneously, in which case the loss of energy would be represented by a compound clang or a group of spectrum lines. But in the atom case we are not dealing with a single atom, we are dealing with a multitude; so that some of them may be in one condition and some in another. The compound spectrum does not emanate from a single atom, but from a large number; and the intensity of the different lines are regulated by rather abstruse considerations of probability, based on temperature and other physical conditions.

CHAPTER XIV

RETURN TO ELECTRONS AND ATOMS AND QUANTA

It does not follow that all possible orbits contain an electron revolving in them; many of them are only possible, not actual, paths. Electrons have choice of many paths, and may occupy some and not others. In a hydrogen atom, for instance, the paths are many, but the electron is only one. Shall it take one of the inner or outer paths? They are labelled, from inner to outer, *K*, *L*, *M*, etc., or 1, 2, 3, etc., and in any selected hydrogen atom any one of these may be occupied.

When an electron jumps down from one ring or orbit to another, it emits wave energy at a frequency of vibration depending on the step it has taken; the amount of energy emitted being also proportional to the step. The different orbits are characterised by different energies, which are inversely as the radii. And the radii are all different. So the frequencies of vibration characteristic of the different drops will likewise be all different. Hence the multiplicity of possible lines in the spectrum whenever the possible orbits are brought into use and made actual.

The remarkable thing about these possible orbits is their lack of continuity, the absence of anything connecting them, or apparently of anything between them. Why does an electron jump from one to another and then settle down? The evidence that it does so is clear, because that hypothesis corresponds to the phenomena observed, and accurately accounts for the lines in the spectrum, with remarkable precision. But what the peculiarity in the interior of the atom may be, which permits or enforces this discontinuous behaviour, is at present unknown. Nor do we know why anything less than a complete jump either never occurs, or never produces any perceptible effect. An electron either jumps and emits a quantum of energy, or it does nothing. It is unresponsive to any stimulus too weak to precipitate it from one orbit to another. Ordinary perturbations and oscillations do not seem to occur, or do not exhibit themselves.

To realise the kind of conditions which make such response at a critical point alone possible, it may help if we think of other discontinuities or quanta-like operations in ordinary life.

Ordinary Examples of Discontinuity

To illustrate further the kind of discontinuity which the quantum represents, by examples drawn from very ordinary experience, one might use illustrations like this. A block or pillar set up on a table can be upset by a critical force applied to it horizontally at a sufficient elevation; but any force less than that, applied at the same point, need not cause any disturbance, and certainly will not upset it. The upset is a sudden or discontinuous result achieved by a definite force; and any force greater than the critical value can do no more than upset it, unless it is a blow violent enough to topple it over a second time. If we could only detect a topple-over, and nothing less, we might say it was regulated by quanta.

Or take an explosive substance, say gunpowder. A spark of sufficient suddenness will ignite it and produce a violent result; a stronger spark will do no more; but an unsuitable spark or flame will do nothing.

Or, again, take an example from agriculture. A seed thrown into the ground will germinate and produce a bush or tree of appropriate size. But half a seed would presumably decay and produce nothing. Indeed, seeds may be said to exist in quanta: though of course a potato, which is not a seed but a tuber, may be effectively divided, provided each portion contains the germinating quantum in the shape of the vesicle called an " eye."

Again, a clock gives time in quanta. The hands of the clock do not move continuously, but in jerks: and if the pendulum oscillates insufficiently, so that the escapement fails, they do not progress at all. If the pendulum is swung more violently, the clock still goes at the same rate. The time-keeping quality depends, not on amplitude of the pendulum vibrations, but on their frequency. So impressed are some people with the discontinuous character of clock indication that they have begun to suspect that time itself was discontinuous, just as some people were ready to suppose that energy itself was discontinuous. But that is an entire mistake. Time knows nothing about the kind of instrument that we may use to measure it. Undoubtedly it flows quite continuously. We can indeed have continuous clocks, such as water-clocks, where time is measured by the amount of water which at constant level flows through a small orifice. Or again, by King Alfred the Great's legendary candles, which measured time by their burning down.

Matter is discontinuous; and electricity, strange to say, is discontinuous. But time and space—and I should say the ether—are continuous. So is energy in itself; though cartridges contain it in packets and liberate it in quanta. Atoms may do the same, and in that way confer a discontinuous appearance on energy, or at least on radiated energy.

The heavenly bodies are obviously discontinuous; and there must be some reason—which indeed has been partly ascertained—why they are so; and why matter is distributed in the large but limited masses that we call the stars, and not aggregated into one great lump by reason of gravitative attraction.

An agent like light certainly appears to be continuous; though some of its relations with electricity are so peculiar and striking that some have begun to suspect a kind of discontinuity even in a wave front of light. We must leave this, therefore, as an open question. It is improbable, but not impossible, that a wave front is discontinuous or speckled. We must know more about the structure of the ether before we can decide questions of that kind.

Some of the above illustrations may serve to show that there is nothing altogether novel and perturbing in the idea of physical discontinuities like quanta. And every example of their detection in unexplored regions of enquiry must be helpful and instructive, and contributory to further knowledge to a remarkable degree. We may not in every case understand the reason why any particular quantum should exist. We certainly do not fully understand it in the emission and absorption of radiation. But we can be content for the present with the acceptance of the fact—so it be a fact—and hope for further light on the theory in good time. Maxwell's discovery that light was an electromagnetic phenomenon, and shall we say J. J. Thomson's discovery that electricity was discontinuous, are manifest clues tending to diminish our surprise at finding a discontinuity when the interaction between an electron and the ether occurs, an interaction which is known to be responsible for the emission of light.

X-Rays also furnish us with a further very instructive example. Every pulse of *X*-rays is generated by the sudden stoppage of an electron. In a highly rarefied vacuum-tube, such as was introduced by Sir William Crookes, a torrent of electrons is projected from the cathode at enormous speeds; and then on striking a massive target they are suddenly stopped. Every stopped electron emits a pulse of *X*-rays; somewhat as a cannon ball striking a sheet of steel armour emits a flash of light. Hence *X*-rays manifestly have a discontinuous origin; and they carry with them the marks of this origin; for when they impinge on a suitable substance they are able to eject an electron from it, having in its speed and general behaviour many of the characteristics of the electron whose stoppage generated the rays. And the strange thing is that a specific *X*-ray, generated by the stoppage of an electron with a given amount of energy, can eject an electron with practically the same amount of energy; even when, by reason of distance of travel and other enfeeblements, its own energy has grown so weak that one would not have expected it to be competent to do anything so energetic. But through all its enfeeblement it retains traces of its origin: we may liken it to a small seed which has undergone many vicissitudes and never seemed very strong; for a seed, if it fructifies at all, is able to reproduce a plant of the same kind as that which originated it: it can do either that or nothing. And radiation quanta are in somewhat the same predicament.

In a paper read before Section A of the British Association at Edinburgh, in 1921, Professor C. G. Darwin briefly summarised the main outlines of the quantum rule or theory as follows:—

"The essential feature of the theory is the existence of a universal constant, the quantum $h = 6{\cdot}55 + 10^{-27}$ erg sec., which in some way, not yet explained, controls exchanges of energy. The simplest form of the rule is that if energy is exchanged with a system of frequency ν vibrations per second, then it will be exchanged in amount $h\nu$. Its application is at present only known for periodic systems. The photoelectric effect is the simplest case. Here light falls on a metal surface and in the act electrons are emitted with a high velocity. Their energy is connected with the frequency of the light by the quantum relation. The same effect, enormously enhanced, is found with the *X*-rays, and here the converse effect is also found—that electrons of given energy can only excite *X*-rays of frequency below a certain amount.

"It was in the radiation theory that Planck discovered the quantum. It works in exactly the same way, though here complicated by the conception of temperature. It was in this connection that Poincaré proved that anything even remotely resembling the facts of radiation could only be explained by precisely Planck's ideas."

CHAPTER XV

SPECTRUM LINES AS RELATED TO ORBITS

Elementary Descriptive Summary

We can now summarise matters pretty simply for at any rate the simplest kind of atom. No atom can be simpler than the hydrogen atom; consisting as it does of one positively charged nucleus at the centre, and one negatively charged electron revolving round it, in one of the possible paths or permissible orbits which for some unknown reason surround the nucleus, and in any one of which the revolving particle can remain permanently circulating without loss of energy, so long as it is not disturbed.

These possible paths or permissible orbits are Bohr's fundamental contribution to the structure of the atom. They represent the kind of discontinuity or quantum relation which he was the first to introduce, or rather to discover. He discovered the fact, and we are unable at present to assign the reason.

The possible Bohr orbits may be numbered, starting from the centre, as 1, 2, 3, 4, and so on; their radii being 1, 4, 9, 16, etc.; and there are no intermediate orbits between them in which the particle is able to exist. If it leaves one orbit it must go to another. Or, of course, it may go away altogether; in which case the atom is no longer neutral, but is said to be "ionised," being broken up into two portions, positive and negative respectively, of very unequal mass though of equal charge. The nucleus and an electron are separated, until under some influence they re-combine once more into a neutral atom. A certain amount of energy must be supplied to effect this ionisation. The electron has as it were to be torn or jerked out of one of its stable positions, even if it only rises into some outer orbit; or if sufficient energy is supplied it is jerked away altogether, and the atom is ionised; the ions being the two separate charges.

If an electron is revolving in one of the outer possible orbits it will be more easily jerked away than if it is in one of the close inner ones. And if it is revolving in one of the very large orbits, very little disturbance is wanted to remove it altogether: in that condition any kind of collision with other atoms is liable to separate it. Consequently, in ordinary hydrogen we must not expect to find the outermost orbits occupied. They represent a possibility which is not utilised. The condition is too unstable for permanency. Separation is too easy. Only in a very rarefied condition of the gas, when collisions are infrequent, could we expect to find these very outer orbits sometimes occupied by the revolving particle. Such a condition of things might occur in a highly rarefied vacuum tube, or in a highly rarefied nebula, where the particles are comparatively few and far between. In ordinary gas, as we know it, under atmospheric pressure, only the inner orbits could be occupied; and in the majority of cases it may well happen that most of the hydrogen atoms have their single electron revolving only in the innermost orbit of all. For there it is least subject to disturbing influences, and there it has a minimum amount of potential energy. To get it out of that orbit some energy must be supplied. It cannot get out of itself. It is like water at the bottom of a hill; it may be running fast, but it cannot get up the hill again unless it is pumped.

Some energy must be supplied to raise the particle from any inner orbit to any outer one. And, conversely, if the particle drops from any outer orbit to any inner one, some energy must be emitted or radiated away.

The peculiarity is this: that if radiation of inadequate frequency of vibration is supplied, it cannot even change the particle from one orbit to the next, it will be ineffective and achieve nothing. The particle takes no notice of any but a whole quantum of energy. Conversely, unless the particle is able to drop from one orbit to the next, it emits no energy. It cannot emit less than a quantum.

But we are not to suppose that the same amount of energy is needed for the step between every two consecutive orbits. The quanta are not all the same size. To remove a particle from orbit 1 to orbit 2 needs a large quantum. To remove one from orbit 5 to orbit 6, quite a small quantum suffices. The quanta vary in size according to the rapidity of revolution of the particle, or at least according to some rate of vibration connected with that rate of revolution. There is indeed a quantum constant, the thing which Planck called h. But to get the step of energy which will raise a particle out of any orbit, we must multiply this h by a characteristic rapidity or frequency, which is called ν. So that the step of energy is $h\nu$. And the radiation which is emitted is found to have this same frequency of vibration; which determines, and is measured by, the position of its spectrum line.

The spectrum lines, therefore, which are emitted by a particle disturbed from the innermost orbit represent a very rapid vibration, and will be high up in the ultra-violet part of the spectrum, or perhaps will be in the region where we only know them as X-rays. On the other hand, the spectrum lines corresponding to some outer orbit, say the fourth, will be far down in the spectrum below the red, the fourth being lower than the third. The frequency of vibration connected with the second orbit of the hydrogen atom are in the visible part of the spectrum, and constitute the well-known spectrum of hydrogen, with lines in the red, the green, and the blue, called by Fraunhofer C, F, and G. These lines represent part of the series belonging to the second orbit. The series belonging to the first orbit was predicted as far up in the ultra-violet, and was afterwards observed by Lyman, and is known as the Lyman series; though the theory had accounted for, or at least expected, those lines before they were discovered. The series associated with the third orbit of hydrogen is in the infra red, and had already been observed by the spectroscopist Paschen. Those hydrogen spectra are the most familiar and typical series, known to everybody who has looked into the subject at all. And they may stand as the type of what is to be expected in other cases.

It should now be asked, however, if each set is connected with one orbit, why should they constitute a *series* of lines? Why not only one line?

Well, if the particles all came from one place or one distance from the nucleus, and dropped thence, say, into the second orbit, their radiation would constitute one line. But they are not limited to one original place. They might drop from orbit 3 into orbit 2. But they could also drop from orbit 4 into orbit 2; or they might start from orbit 5. In other words, they may drop more than one step. And if they drop more than one step their quantum of radiation, and accordingly their frequency of vibration, will be increased. Dropping from orbit 3 into orbit 2 gives the line *C*. Dropping from orbit 4 into orbit 2 gives the line *F*, while dropping from 5 to 2 gives the line *G*. This is for the best known case of hydrogen. If none of the atoms contain particles revolving in orbit 5, they naturally cannot drop thence: and then the line *G* will not appear in the hydrogen spectrum. And if in the hydrogen under observation there are no particles revolving in any orbit outside 5, then no higher lines will appear. But if one takes hydrogen under such strongly agitated conditions, by reason say of high temperature, that the atoms are nearly ionised, there may be particles in many of the outer orbits, and then we shall be able to get the higher lines of the series; as we do in what is called a "spark spectrum," where the disturbance caused by the spark is of ionising quality. The highest possible line of the *visible* series will be got when the particle drops from infinity, that is, from any reasonably large distance, into orbit 2. And that is the termination or head of that series, such as was depicted in the diagram on page 117, and it represents the highest frequency associated with orbit 2. This series is denoted by the letter *L*.

If we are to get lines higher than that, we must have particles dropping from different distances into orbit 1. But then they will be lines belonging to a different series altogether, the *K* series, and will be essentially of a much higher frequency. Orbit 1 is what usually gives the *X*-rays, or at any rate the high ultra-violet portion of the spectrum. The lowest line of this series will correspond to a drop from 2 to 1. The next line will be a drop from 3 to 1. The next line from 4 to 1. And the head of the series will be given by the drop from infinity to 1; that is to say, when an ionised or separated electron drops in and becomes part of the system again. An ionised or separate electron dropping in will always give the head line of the series:—the top series if it drops into orbit 1, a middle series if it drops into orbit 2, a lower series if it drops into orbit 3; and so on.

To make this quite clear, then, we can say that the series is determined by the orbit into which a particle drops; while the position of a line in the series is determined by the radius of the orbit whence it drops. The lowest line represents a drop from one orbit to the next. The highest line, or head of the series, corresponds to a drop from infinity, or the reunion of an ionised particle.

The same sort of thing may be said for absorption. For just as the sudden movements of electrons excite radiation of definite frequency, so the supply of radiation from an outside source, at definite frequency, excites a jump of electrons. Absorption or gain of energy makes them jump outwards, but unless the right frequency is supplied they will not jump at all. To make a particle jump out of orbit 1 needs a very high frequency of vibration, ultra-violet at least, and perhaps *X*-rays. The characteristic frequency for a given orbit depends on the atomic number of the particular chemical element to which the atom belongs. To make it jump out of orbit 2, in the case of hydrogen, the frequency of visible light may suffice. But unless the right frequency is supplied, nothing would happen, and no radiation would be absorbed; it would simply pass on.

Under what conditions, then, can radiation of low frequency be absorbed? Suppose such a frequency as would correspond to a particle in orbit 6. There may be no particle in orbit 6, or in any orbit outside that. In that case there would be nothing able to absorb the radiation, and no effect would be produced: nothing would happen, the atom would take no notice. But indeed in normal hydrogen, as we know it, there may be no particle in orbit 3, or even in orbit 2; no such particle in any of the atoms, or not in any such number of atoms as would enable observation to be made. In that case, then, nothing would happen either.

But every neutral hydrogen atom must contain its one electron somewhere. And the probability is that they will all contain their electron in orbit 1, because that is the place where the residual potential energy is least, and where an electron may have settled down in permanent fashion. The only kind of radiation which can eject it out of that orbit is the high ultra-violet kind, which has some relation to the revolution frequency of that orbit. If a quantum of this particular kind of radiation is supplied, the particle will jump from orbit 1 to some outer orbit, depending on whether energy of the right frequency is supplied. And if radiation of sufficient rate of vibration is supplied, it will jump away altogether, or the atom will be ionised.

The question naturally arises, Can an electron drop below the innermost or *K* orbit? If it did it would have apparently to drop into the nucleus, for there is no intermediate stopping place, unless we allow fractions. If any radiation of excessively high frequency is ever observed it might be called *J* radiation, and it is understood that Prof. Barkla is looking for it; having already found an odd and unexpected discontinuity which demands explanation. But what the explanation is, and whether there really is any *J* radiation, remains for future discovery and announcement. The nearest approach to it at present is the gamma radiation, which is emitted by a convulsion of the nucleus. I suggest that gamma rays due to spontaneous ionisation may be the head of a *J* series, and that the rest of the series exhibits itself as secondary and softer gamma rays.

Distance of Stars

A very curious application of the fact that fresh lines appear under ionisation, has been made to determine the otherwise immeasurable distance of the further stars and star clusters,—objects which seemed at one time hopelessly beyond human measurement. From the appearance of lines in the spectrum, and their relative intensity, it is possible to infer the state of ionisation in the source which emitted the lines, that is in the star or cluster or nebula, and thus to form an estimate of its temperature and absolute brightness. By comparing its absolute brightness with its apparent brightness, we can get a measure of its distance. This method was tested by application to objects of known distance, and was then extended to objects of unknown distance. The great star cluster in Hercules, which profoundly stirred the interest of Sir Wm. Herschel, is thus estimated to be at a distance of 36,000 light years; while some other objects are reckoned still further away, even as much as a quarter million light years in the depths of space. This is a remarkable application of a detailed study of the enhanced lines due to ionisation by heat, or to excessive rarefaction, or both; and, to understand it further, recent astronomical and spectroscopic papers must be studied. The determination of distance by a method whose validity is irrespective of distance, which can therefore be applied successfully to the most hopelessly distant luminous objects, serves as an illustration of the way in which modern astronomers are able to press every item of new knowledge into the service of their splendid science.

CHAPTER XVI

DIAGRAM REPRESENTATIVE OF THE ABOVE ELEMENTARY SUMMARY ABOUT THE HYDROGEN ATOM

I AM now going to repeat the plotting of spectrum lines depicted in Fig. 7 (page 117) in a rather more elaborate way, so as to show not only the distribution of the lines in the hydrogen spectrum, but also the way in which they originate, that is to say, the orbits from which they respectively drop. I might draw the orbits as circles; but I prefer to treat them as different levels in the atom. Level surfaces, as we know, are always curved in reality; the surface of the ocean, for instance, or of water in a basin for that matter, is spherical though it is commonly thought of as flat. And the diagram is rather simpler to look at if we do not attempt to make a picture of it, but merely draw the different levels.

The lowest level corresponds to the nucleus, which we will not attempt to deal with in this diagram, but simply consider as the lowest level. Above it comes the level of orbit 1, at some distance which we may take as our unit for vertical plotting. At the level 4 comes orbit number 2. At the level 9, orbit number 3; and at the level 16, orbit number 4. The diagram would get confused if I introduced more of the orbits; so they must be understood.

Horizontally are plotted the frequencies of vibration of the different lines in the spectrum. They are plotted to scale with the numbers attached, reckoning from the zero point, on any convenient scale. Three series of lines (K, L and M) are represented. The first, which is of high frequency, on the right of the diagram; the second, of medium frequency, in the middle; and the third, of lower frequency, on the left. The numbers attached to these lines (written along the bottom level) are 7 and 16 for the third series; 20, 27, and 36 for the second series; and 108, 128, 135, and 144 for the first series. The lines are spaced out in accordance with these numbers, though they are not drawn only as lines, but as arrows—for a reason which will be manifest directly.

The lettering of the lines, A, B, C, etc., corresponds with the lettering on page 117. It would confuse the figure to draw the lines D, E, F, etc.; so only the head of the series, Z, is drawn. The others are merely indicated, in the space between C and Z.

DIAGRAM ILLUSTRATING THE PRODUCTION OF SPECTRAL LINES BY THE DROPPING OF ELECTRONS FROM DIFFERENT LEVELS INSIDE THE HYDROGEN ATOM.

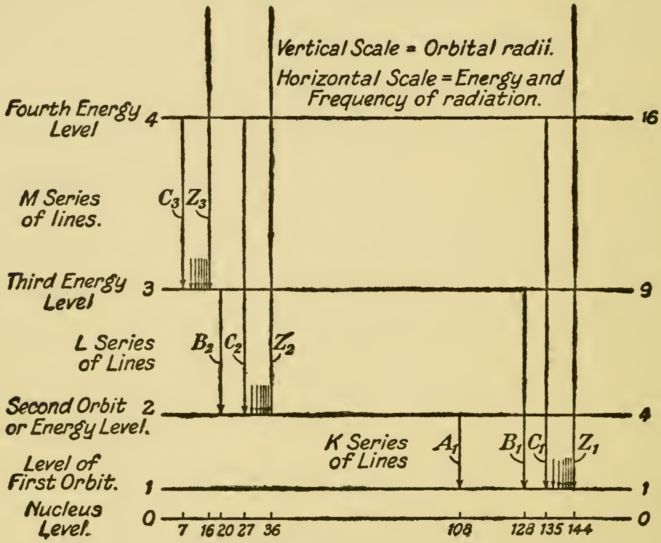

FIG. 8.

The numbers written on the horizontal scale at the zero or lowest level, vertically below the corresponding lines, give the relative frequencies (or inverse wave lengths) of the spectral lines, in the three different series shown. Z is the head of each series, and its arrow comes down from infinity. The numbers also represent the relative energy emitted by each electron during its drop along the arrow. An equal amount of work is required to reverse its motion.

So far there is not much difference between this diagram and that in Fig. 7. But now comes the meaning of the arrows. They are the important things. They represent the dropping of an electron from one level to another. Their length does not mean anything particular, but the feather of the arrow shows whence the electron has come, and the head of the arrow shows whither it goes; so that each arrow stretches from the level of the source, or initial orbit, to the terminal orbit in which it takes up its new position. We see, for instance, that the line A_1 is emitted by an electron which drops from level 2 to level 1. The line in the same series called B_1 is the result of a drop from 3 to 1. The line C_1 is emitted by an electron which has dropped from 4 to 1. The next line (not fully shown) would have dropped from 5 to 1. And so on; till you come to the final line of the series (the one labelled Z), which has dropped from infinity, that is from some yards above the paper. These are all the lines in the first series—the high frequency or ultra-violet series. And the numbers below them represent not only the frequencies of the lines, but also the energies emitted per atom by the respective drops. This series is technically known as the K series. And the line Z in the K series is the highest possible for any given atom. The number 144 represents the energy of this drop; and it also represents the energy of ionisation, that is to say, the energy which must be supplied to an electron at the level 1 in order to throw it out of the atom altogether, to fling it to infinity. If the energy supplied, instead of being 144, is only 135, then the electron would be tossed up on to the fourth level: and if only 128 is supplied, it will climb to the third level; while 108 would only toss it up to the second. Anything less than 108 will do nothing to an atom on the first level: there is no place at which it could rest. If it is disturbed at all, it returns instantaneously, producing, so far as we know, no perceptible effect. The numbers given, 108 to 144, represent the effective quantity of energy which can be absorbed by an electron in the first orbit, just as they also represent the energies which a returning electron, returning from one or other of the different levels, would give out on reaching the first orbit.

Now attend to the second series, technically known as the L series of spectrum lines. The lowest line B, corresponding to the frequency and energy 20 (on the same scale as before), is the result of a drop from the third level to the second. A drop from the fourth level to the second will give the line C, of frequency and energy represented by 27. The next line, not shown or only just indicated, would have the frequency 30·24. The next one 32. And so on, till you come to the head of the series, which represents the ionisation energy for electrons at the second level; or the frequency emitted or absorbed by a transit to or from the second level from or to infinity, with the frequency and the energy 36; which is a quarter of the ionisation energy required by a particle in orbit 1.

The third series of lines, rather lower down the scale, and below the red of the visible spectrum, hardly needs further explanation. The lowest, or C line, corresponds to a drop between consecutive levels. The other lines proceed with exactly the same intervals as in the other cases. And the head of the series, Z, represents the drop from infinity to the third level. Or conversely, the ionisation energy at the third level.

The whole diagram should now be clear, and to show any more would be merely confusing.

CHAPTER XVII

ELEMENTARY QUANTITATIVE SUMMARY

So far we have dealt with the simplest kind of atom in a descriptive manner, without much calculation. But we can now introduce Bohr's numerical relation between the orbits, and become more definite. In the series of possible paths or permissible orbits, which we numbered 1, 2, 3, 4, etc., these numbers do not represent their radii. Their radii do not increase in arithmetical progression. Successive radii are represented by the square numbers, 1, 4, 9, 16, 25, etc. And accordingly the total (expended or negative) energy corresponding to each orbit—which we know to be inversely as the distance, that is inversely as the radius of the orbit, in accordance with Newton's laws—will be represented by the series of reciprocals of those square numbers. In other words, if the total energy associated with orbit number 1 is called 1, the total energy in orbit number 2 will be $\frac{1}{4}$. So that the step of energy from 1 to 2 will be $\frac{3}{4}$. Again, the energy in number 3 will be 1/9th. So that the step or difference of energy from 1 to 3 will be 8/9ths. While the energy of the step from 2 to 3 will be 1/4th—1/9th, that is to say, 5/36ths, or roughly about 1/7th.

The energy in orbit 4 will be 1/16th, so that to make the particle jump from 1 to 4, 15/16ths of its energy must be supplied to it. A very little more therefore would enable it to escape altogether. And accordingly, when the right kind of energy is supplied, some of the particles do escape. But not all of them. Some may rise temporarily into higher orbits and then drop back again; thereby giving the line of the spectrum corresponding to the drop. Hence if we want to see these lines we must put the gas under ionising conditions. And then we may be pretty sure that while some of the atoms are ionised altogether, others will be left in intermediate stages, whence their mutual perturbations and collisions may drive them back; and most probably they will go back into the normal state, the most stable and permanent condition, represented by their occupying orbit number 1. Such an ionised gas would have some kind of absorptive quality restored to it. For some of the outer orbits which had previously been empty would now be occupied by a particle endowed with a slowness which makes it capable of absorbing light of even moderate frequency.

Consider now for a moment, not the energy only, but the frequency or rapidity of revolution of the particles in the different orbits, and at what speed they are revolving. For simplicity we may as well take each orbit as circular; though as far as the theory goes, it might equally well be elliptical, in which case what we call its radius would mean its semi-axis major. But to deal with elliptic orbits numerically is more complicated, because the speed is different in different parts of the orbit; so that we should have to be more careful in specification. For illustrative purposes it is sufficient to think of circular orbits. Now the speed in a circular orbit will be the circumference divided by the time of revolution. And the time of revolution will be dependent on the radius, or distance from the centre, in accordance with Kepler's Third Law; or, what is the same thing, Newton's Law that the centripetal force is equal to the attraction :—

$$\frac{mv^2}{r} = \frac{Ee}{r^2},$$

or

$$rv^2 = \frac{Ee}{m} = \text{a constant.}$$

That shows how the speed is related to the radius. And since the radii go as the square numbers we can easily reckon how the speeds go. They will be inversely as the simple numbers, that is to say, 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$. While the frequencies, or reciprocals of the time-period, will be as the inverse cubes, 1/8th, 1/27th, 1/64th, etc., showing what a much higher frequency is necessary to disturb a particle in one of the inner orbits than in one of the outer ones. Indeed, particles in the outer orbits are so easily disturbed that they are seldom found there. The only reason why you do not disturb a particle in the outer orbit is because under ordinary circumstances it is not there. You may find it there in very rarefied air, and you may find it in ionised gas. Otherwise you need not expect any phenomenon connected with its disturbance to appear. Particles in number 1 orbit are always present; at least in the greater number of the atoms. That is their normal position. But then they are very stable there, and not easily perturbed. Nothing but direct violence, such as the impact of a projectile, or else a quantum of radiation of adequate frequency, is able to perturb them.

Absolute Values

We are not limited, however, to the discussion of the proportional relation existing among the frequencies and the energies in the different orbits; we can reckon their absolute values, in terms of constants measurable in the laboratory, especially in terms of the Balmer constant B and the Planck constant h.

For we know that the frequency associated with the step, say, from orbit 2 to orbit 4, is

$$\nu = B\left(\frac{1}{4} - \frac{1}{16}\right).$$

And we know that the amount of energy associated with the same step is $h\nu$; that is to say, that the step of energy is equal to

$$Bh\left(\frac{1}{4} - \frac{1}{16}\right).$$

This important expression is general. All that differs about it in different cases is the numerical part. A more general value would be denoted by

$$Bh\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right).$$

The amount of energy that has to be supplied to take an electron from orbit 1 to orbit 2 is $Bh\ (1 - \frac{1}{4})$. And this is the amount of energy which will be emitted when the reverse step is taken. The amount of energy required to shift a particle from orbit 2 to orbit 3 is $Bh\ (\frac{1}{4} - \frac{1}{9})$. And this also will be the amount of energy emitted when a particle drops back from 3 to 2, the frequency of the radiation emitted being that corresponding to Fraunhofer's line *C*, the lowest line in the second series. Of course, the actual amount of energy that goes to form this line will depend on how many electrons are performing this evolution. That is not a matter that we can discuss further here. The question of probabilities enters into the intensity or brightness of the various lines. We must be sure that there are particles in orbit 3 before they can drop out of it. If very few of the atoms contain such particles, the corresponding line will be faint. And if any of them drop to orbit 1, they would not give line *C* at all, but a line in the ultra-violet.

Return from this digression to the step of energy from any one orbit to any other. It is, we see, always expressible by *Bh* multiplied by a certain relation among integers, the difference of the reciprocals of two squares. Let us consider then the amount of energy needed to turn a particle out of orbit 1 into any of the outer orbits. It will either be $Bh\ (1 - \frac{1}{4})$ or $Bh\ (1 - \frac{1}{9})$ or $Bh\ (1 - \frac{1}{16})$ and so on. Hence how much energy is needed to get it out altogether? A very little more suffices, namely, $Bh\ (1 - \frac{1}{\infty})$, which is simply *Bh*. That gives the amount of energy needed to eject the particle from orbit 1, and take it out of the atom altogether. In other words, *Bh* is the maximum ionisation energy per atom, the energy needed to ionise an atom of normal hydrogen with no electrons in any of the outer orbits.

To ionise an atom whose electron was in the second orbit, a quarter of this energy would suffice. To ionise an atom whose electron was in the third orbit $\frac{1}{9}Bh$ is all that is wanted. Hence particles are easily extracted from outer orbits;

and consequently are seldom there. But they must be there in order to give the corresponding lines in the spectrum. Hence it is that the spectrum of hydrogen differs under different conditions. And hence it is that by choosing the conditions carefully, Professor R. W. Wood, of Baltimore, looking at hydrogen in a vacuum tube far away from the disturbing influences of the electrodes, was able to see spectrum lines in great number, such as are not often seen, representing droppings of particles from a multitude of outer orbits into orbit number 2; since it is only orbit number 2 which would give the right series of frequencies for ordinary eye-vision.

CHAPTER XVIII

OTHER ATOMS

So far we have dealt only with the simplest possible kind of atom, the hydrogen atom, with a single nucleus and a single revolving particle. When we come to other atoms, with a compound nucleus and many revolving electrons, the conditions become more complicated and the theory less simple. Each atom has an atomic number, which we will call N, which specifies the positive charge on the nucleus and the corresponding number of planetary electrons. The aggregate charge of the compound nucleus is Ne, and this is neutralised so far as outside the atom is concerned by the N revolving electrons, to which we may try to apply a modified sort of gravitational theory, for they are like planets revolving round an extra massive star and interfering with or perturbing each other. Extraordinary progress has been made, but there is much more to be done. It is hardly possible at present to deal *fully* even with the atom next most simple to hydrogen, namely, the helium atom; which has a double nuclear charge, and, in the normal condition, two electrons revolving round it. But an odd possibility now presents itself, namely, that one of the electrons may be absent. The helium may be half ionised; not reduced to nothing but the nucleus, but reduced to the double nucleus and a single electron, so that perturbations will be absent. In that case, the single electron will find itself as if under the influence of a hydrogen nucleus of double power, and may thus be tempted to emit a spectrum very like a hydrogen spectrum as one of its series. That is indeed exactly what it does. It gives a spectrum so like an exceptional kind of hydrogen that for a long time it was thought to be hydrogen. And the genius of Professor Bohr was necessary to decipher its real meaning and decide that though its lines coincided with a certain quasi-hydrogen series, yet they were due not to hydrogen at all, but to helium—a fact which the great spectroscopist Fowler subsequently completely verified. But it was rather puzzling, because the series does not appear in ordinary helium. The helium has to be half ionised; and consequently it only appears when hydrogen is present. Hence no wonder it was thought to be due to hydrogen. It is thus in a manner indirectly due to hydrogen; but it is only due to the hydrogen's ionising power. The spectrum itself emerges from the helium atom; an electron in a helium orbit behaving like an electron in an intermediate and impossible half-way orbit of hydrogen. For though it has a double rv^2, because of the double central attraction, this is not obvious. Its rv or moment of momentum is just the same as in hydrogen. This quantity proceeds by steps or quanta, $h/2\pi$, or what we called A; and its quanta are just the same in helium as in hydrogen; the same indeed in every atom of the series. It is independent of the atomic number or nuclear charge N. The orbital radii will be more crowded together, for they depend inversely upon N, but the velocities are directly proportional to N; so, from the product rv, N cancels out. The energies and frequencies are proportional to N^2. Hence when we observe an N^2-fold frequency, we need not attribute it to a hydrogen atom with impossible fractionally-numbered orbital radii $n + \frac{1}{N}$, but to an N times strengthened nucleus, with its orbital angular momenta, and radii, and everything, in regular integral succession as usual.

We return to this subject of ionised helium in Chapter XXIV.

Partial Treatment of Heavy Atoms

Of a complex atom, the innermost orbit, and the K spectrum corresponding thereto, are likely to be much simpler than any of the others, since those others will be complicated by including the orbits of other electrons. In any outer orbit, that is in any but the innermost one, the radius vector, as it sweeps over areas, sweeps not over free space but over space containing singular points, which are electrical charges. The field of force therefore contains not only attraction, but repulsion too. The repulsion exercised by these distributed charges tends to diminish the attractive force of the central nucleus. But it is only those which are swept over by the radius vector which are really effective, or, so to speak, troublesome. Hence to the innermost orbit this complication does not apply, or only applies in very minor degree because of the discontinuous character of distribution of the particles outside.

The rapidity of revolution in the innermost orbit of an atom of high atomic number N, depending as it does upon N^2, will be very high. And accordingly its radiations are only likely to be known to us as X-rays. For hydrogen indeed its K spectrum comes into what is recognised as an ultra-violet portion of the luminous spectrum; because for hydrogen N is only 1. But for all the other elements it is much higher. Even for helium it is four times higher. While for uranium it will be 92^2 or 8464 times as high as for hydrogen.

But, high or low, it is likely to be the simplest spectrum which heavy atoms can emit. X-Ray spectra are known to have fairly simple laws: and it was this which enabled Moseley to measure N with such certainty, and to construct the staircase of elements with equal steps. The ladder of frequency is climbed, by the different elements of the atomic series, in regular steps of equal magnitude. And the height in the spectrum corresponds to the atomic number. The atomic number, and therefore the nuclear charge, is given by the square root of the X-ray frequency. It was the simplicity and regularity of the X-ray spectrum of different elements that enabled Moseley to confirm so definitely the previously guessed importance and significance of the atomic number, as more immediately vital to chemistry and spectroscopy than the atomic weight. Anything may interfere with atomic weight; and one may even have different atomic weights for one and the same chemical element. But the nuclear charge determines the atomic number, and that determines the number of revolving electrons; and naturally it is always an integer. That is what Moseley proved.

And now, as we may remark incidentally, strange to say, Aston has proved that atomic weights are integers too, up to a certain limit of accuracy, being all of them simple multiples of hydrogen in the bound condition—that is to say, the condition in which we encounter it hypothetically in the nucleus of helium; and, less hypothetically because more demonstrably, as it is encountered in the nucleus of many of the other elements.

The clear experimental demonstration of the integer value of atomic weights proves that all atoms are built up of protons and electrons. The atomic weight counts and expresses the number of protons in the nucleus,—not the unbalanced or effectively charged ones only, but the total number. Electrons add a little to atomic weight, but very little, because they have so little inertia or substance. The massiveness of a proton is surprising.

We may return to this when we deal with helium and other atoms more in detail,—and especially if and when we ever deal with the properties of Ether,—but will now attend to absolute and not merely relative or proportional values for the different atomic quantities and calculated spectrum frequencies.

What can be done with atoms heavier than hydrogen and helium is hinted at at the end of Chap. XXI, page 176, and at the end of Chap. XXIII, page 185.

CHAPTER XIX

ABSOLUTE VALUE OF THE RADIATION-FREQUENCY OR CALCULATION OF THE BALMER OR SO-CALLED RYDBERG CONSTANT

HITHERTO we have said that the frequency of vibration responsible for the occurrence of a sharp line in a spectrum was proportional to a difference of reciprocals of squares of integers; or, as we wrote it in Chaps. X and XVII, that the frequency—or reciprocal of wave-length multiplied by the velocity of light—was equal to

$$B\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right).$$

We have already dealt with the numerical portion of this expression, and must now concentrate on its absolute value, that is, on a determination of the constant B, which—either as B or as B/c—is known as Rydberg's or Balmer's constant. By applying very simple dynamical considerations, such as we have now rather elaborately paved the way for, we may hope to calculate the value of this constant, in terms of the fundamental electrical and mechanical units, in absolute measure. In this we shall be following Prof. Bohr.

Now Bohr surmised that when atomic energy was radiated monochromatically, or as a definite spectrum line, its emission was due to the drop of an electron from the n_2^{th} possible orbit inside an atom to the n_1^{th}. But he also assumed, what Rutherford had succeeded in demonstrating, that the orbit was described about a centre of force consisting of an opposite charge of electricity in accordance with straightforward electrical attraction subject to the law of the inverse square. It is, therefore, possible to apply astronomical considerations to the revolving electron; or, very simply, to assume a circular orbit as the stable one and equate the centrifugal force to the electric attraction,

$$m\omega^2 r' = \frac{Ee}{Kr^2};$$

where an electron of charge e and mass m is revolving, in a circle of radius r' with angular velocity $\omega = v/r'$, about a central nucleus, of charge E and mass M, at a distance r. The distance r is measured from the small mass m to the centre of the big mass M; while the distance r' is measured from m to the centre of gravity of the two masses, the stationary point about which they are both revolving.

The two distances r and r' are very nearly the same, if M is much bigger than m; but r' really has to be measured to their common centre of gravity. For about that centre they are both revolving, m with radius r', and M with radius r'', such that $r' + r'' = r$, and $r'/r'' = M/m$.

$$\text{Whence } \frac{r}{r'} = \frac{M+m}{M}.$$

This entails a little correction, which, though always small, is not insignificant except for the heavier atoms. In hydrogen, M is about 1840 times m; and the simplest way in practice to apply the correction is to consider that m is not *exactly* the mass of an electron, but, in the case of hydrogen, $\frac{1840}{1841}$th of that mass; and, in general, to interpret the symbol m in the formula as $\frac{M}{M+m}$th of the true m. This will avoid the necessity of repeating this trifling but significant correction in future formulæ. And we can write the above equation, with the understanding that the corrected value of m is to be used,

$$mr^3\omega^2 = Ee/K.$$

The only thing further to explain is the constant K. It is Faraday's dielectric constant, and represents the connection between matter and electricity—an unknown constant of the ether of space. It is not usual to write it, but to call it 1 for vacuum, which is the convention of the electrostatic system of units. It is interesting to note that on the left-hand side of the above equation all the quantities are mechanical, or concerned with matter, whereas on the right-hand side they are electrical, or concerned with ether. We cannot rationally equate such quantities together without introducing some equivalent for the at-present unknown constant K; though conventionally and henceforward, we may often omit such reconciling constant, with the caution that if K be the constant omitted the units employed must be of the electrostatic, not the magnetic, kind.

Similarly in astronomy we may omit to write the other constant γ, which is not so purely an ether constant, since it is a matter-ether-constant, the one governing gravitation; but when we call $\gamma = 1$, we have to remember that our units of mass thenceforth must be gravitational units. It is always well to remember the existence of the ether-constants γ, K, μ, c; gravitational, electrical, magnetic, and luminiferous; and in theoretical work it is unwise to ignore them. But for practical exposition, and short-hand work generally, it is permissible.

The above centrifugal-force equation is virtually Kepler's Third Law, and may now be written

$$mrv^2 = Ee. \quad \ldots \ldots \quad (1)$$

That is ordinary dynamics. But we know that Bohr postulated an atomic or quantum character for moment of momentum, which we wrote as

$$mvr = nA, \quad \ldots \ldots \quad (2)$$

where n is an integer characteristic of the particular orbit under consideration, and A the indivisible unit. Hence now we have something very instructive and helpful; for we can combine these two equations—that is, we can combine the quantum with ordinary dynamics and obtain a conjoint result—what Bohr called applying a "correspondence principle." Let us write the two equations similarly,

$$\left.\begin{aligned} mr^3\omega^2 &= Ee \\ mr^2\omega &= nA \end{aligned}\right\}$$

and then apply ordinary algebra; so as to deduce at once, quite simply, from these two equations, values for the speed and orbital radii of the revolving electron in any (n^{th}) possible orbit of the hydrogen atom :—

$$r\omega = v = \frac{Ee}{nA}$$

$$r = \frac{n^2A^2}{Eem}$$

$$\omega = \frac{E^2e^2m}{n^3A^3}.$$

Showing, by the way in which n occurs in the three expressions, that the velocities in successive orbits proceed as the harmonic series,

$$1, \tfrac{1}{2}, \tfrac{1}{3}, \tfrac{1}{4}, \text{ etc.};$$

that the radii of successive orbits proceed as the squares,

$$1, 4, 9, 16, \text{ etc.};$$

while the angular velocities or frequency of revolution proceed as the inverse cubes,

$$1, \tfrac{1}{8}, \tfrac{1}{27}, \tfrac{1}{64}, \text{ etc.}$$

This last is very interesting, for it may be remembered (see Chap. XI, p. 121) that we found a numerical inverse cube before, for the slowest of the spectral lines, the one corresponding to $\left(\frac{1}{(n-1)^2} - \frac{1}{n^2}\right)$ when n was big; for it then approached the value $2/n^3$.

It looks as if the angular velocity or frequency of revolution corresponded with this lowest kind of frequency of radiation. Let us assume that, and try to get the absolute frequency constant from it; for the indeterminate and arbitrary n will then disappear. We have denoted this constant by B because I think it should be known as Balmer's constant; for Ritz's and Rydberg's work, however admirable, was surely based on Balmer's discovery of the law of the main hydrogen series. And we have written for the frequency of radiation, in general,

$$\nu = B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right).$$

So now we have these two expressions :—
For the lowest frequency of radiation in outermost orbit,

$$\frac{2B}{n^3};$$

and for the frequency of revolution in any orbit,

$$\frac{\omega}{2\pi} = \frac{E^2e^2m}{2\pi n^3 A^3}.$$

Let the two frequencies for some one orbit be the same, then

$$B = \frac{E^2e^2m}{4\pi A^3},$$

a remarkable expression which, being constant, must apply not only to one but to every orbit, and which, if correct, could not possibly come out right by chance. If it be tested, by inserting the experimentally measured values for E, e, m and A, or as it is commonly called $h/2\pi$, on the one side, and the observed position of lines in the spectrum as fixed by $B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$ on the other, they agree exactly. So exactly that in the case of hydrogen we must be careful to use, not m, but the corrected value $m \div \left(1 + \frac{M}{m}\right)$. That is to say, the agreement is even closer than 1 part in 1840 (cf. p. 189).

The constant B was at first known only as the coefficient of the numerical part of the expression which gave the frequencies of vibration corresponding to all the spectral lines; but now it is accounted for, rationally and dynamically, on orthodox electrical and mechanical principles, given only a definite fundamental assumption and introducing the quantum.

This evaluation of the Balmer or Rydberg constant by pure dynamics was a tremendous triumph for Professor Bohr, and may be said to herald the beginning of the Newtonian era in atomic astronomy.

Relation between Energy and Frequency

But we need not stop there. We can calculate the kinetic energy of an electron when moving in any given stable orbit. For its energy will be $\frac{1}{2}mv^2$; and that we will call W. Hence

$$W = \tfrac{1}{2}m\left(\frac{Ee}{nA}\right)^2,$$

n being, as usual, the integer number of the orbit.

So now we can calculate the difference of energy between one orbit and another; let us say between the n_1^{th} and the n_2^{th}. The energy in the outer orbit being W_2 and in the inner orbit W_1,

$$W_1 - W_2 = \frac{E^2e^2m}{2A^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

an expression exceedingly like one that we have seen before in connection with frequency of vibration, which we had better call ν as usual.

$$\nu = B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) = \frac{E^2e^2m}{4\pi A^3}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right).$$

What now is the difference between this ν and what we have just reckoned as $W_1 - W_2$? We see that the only difference is that one contains $2A^2$ in the denominator, while the other contains $4\pi A^3$. They differ only by a constant $2\pi A$, which it is customary to denote by h. Hence they point to the very same truth as that postulated by Planck, who approached the subject from a different point of view, viz., that the energy emitted is proportional to the frequency, or inversely as the wave-length, and that

$$W_1 - W_2 = 2\pi A\nu = h\nu.$$

A beautiful result !

This is so important that a repetition is permissible. For a student is apt, more than once, to wonder why energy should be emitted when an electron drops from an outer to an inner orbit, when actually in the inner orbit it has more energy than it had in the outer one. We must remember that in the fall it gained so much energy that it had a surplus to emit; that is the result of simple mechanical considerations. What is not the result of such considerations is its power of taking up a new orbit. But, granting that it does, the energy gained in the fall is double the difference of energy possessed in the two orbits, exactly double (see Chap. XII). We have shown that the energy gained is $m(v_1^2 - v_2^2)$, while the balance of energy retained is $\frac{1}{2}m(v_1^2 - v_2^2)$, hence an amount equal to this latter balance must be radiated away; and it is radiated away at the frequency ν, so as to satisfy the equation

$$\left.\begin{array}{l}\text{Energy radiated by the step} \\ \quad\text{from any orbit 2 to any} \\ \quad\text{inner orbit 1}\end{array}\right\} = W_1 - W_2 = h\nu$$

where h is Planck's constant or 2π times the unit of angular momentum.

CHAPTER XX

IONISING OF ATOMS

THE Balmer constant B is of the nature of a frequency. The frequency of a spectrum line is always B multiplied by a numerical fraction. That fraction is 1 for a particle falling from infinity into the innermost or K orbit of hydrogen, and accordingly in that case $\nu = B$, the highest frequency known for a hydrogen atom. For heavier atoms, in addition to a fraction, the factor will include the square of their atomic number. So the highest frequency in their case is N^2B.

We have seen (p. 154) that the ionisation energy, or the energy that must be either possessed by or imparted to an atom in order to fling an electron out of it, is always closely related to Bh; the product of Balmer's and Planck's constants. We should remember that, for hydrogen, $B = \frac{me^4}{4\pi A^3}$. Its numerical value we shall give directly. The energy Bh, exactly, will be required to get an electron out of and right away from the K or innermost orbit of hydrogen, $\frac{1}{4}Bh$ out of No. 2 orbit, $\frac{1}{9}Bh$ out of orbit No. 3, and so on.

If we omit the factor h we get the frequency of radiation which would be effective in performing complete ejection, or ionisation, under each of the different conditions, viz., B, or $\frac{1}{4}B$, or $\frac{1}{9}B$, etc.

The ionisation energy of a heavier atom, one with atomic number N, is N^2Bh, or some fraction of it. N^2Bh is approximately the energy required to get an electron out of the K orbit of any atom. N^2B is the frequency of the effective or ejecting radiation; while $N\sqrt{\frac{2Bh}{m}}$ is the speed with which the ejected electron begins to escape.

The other orbits—those outside the prime or K orbit—in the case of heavy atoms, are rather more complicated, and are rather easier to ionise than the simplest theory would suggest; until for the heaviest elements we find that they are liable to be ionised by unknown and apparently insignificant stimuli, and thus, perhaps, it is that they tend to become radioactive with apparent spontaneity. Electrons evaporate from metals at a moderately high temperature. Though certainly true radioactivity involves some kind of explosion of the nucleus, and is not an affair of outlying electrons.

As to the actual values of B and h, and of the product Bh, it may be convenient here to state that the ionisation energy $Bh = 2{\cdot}154 \times 10^{-11}$ ergs, that this corresponds to an electronic velocity of 2190 kilometres per second, and that it represents the effect of a difference of potential of $13\frac{1}{2}$ volts (see below and also Chap. XXI).

Specification of Electronic Speeds in Practice

In dealing with ionisation, and cathode rays, and other electron movements, in the laboratory, the easiest thing to measure and specify is the voltage down which the particle has either really or virtually dropped in order to acquire a given amount of energy.

If the charge e drops down the difference of potential V, it requires energy eV. This follows from the very definition of any kind of " potential," viz., the potential energy per unit charge or mass.

An ordinary falling body starting from one level and arriving at some lower level, no matter by what path (so there be no friction), will acquire a velocity depending only on the vertical height h; in fact $u^2 = 2gh$; which might be written $\frac{2W}{m}$. So also a unit charge travelling down the step of potential V—no matter by what gradient—will gain energy equal to V; and, of course, the charge e will gain energy equal to eV, which may be called W. This energy may be interpreted as $\frac{1}{2}mu^2$, where u is the velocity which the charged particle has acquired under the driving or accelerating propulsion of the electric field. Hence

$u^2 = 2\frac{e}{m}V$; and u and V are thereby so simply and definitely related, that it has become customary to specify either as equivalent to the other. This has become so common that experimenters often speak of a velocity of so many volts, or sometimes of an energy of so many volts. Neither expression is strictly justifiable, any more than other kinds of abbreviated expressions, or slang. It need not be objected to, however, for it is evidently convenient; and we should always be able and ready to interpret it.

The equation $\frac{1}{2}mu^2 = eV$ enables us to convert either velocity or energy into potential or voltage whenever we please, and *vice versa*.

To take an example :—Let an electron be driven by a potential difference of 10 volts, or 1/30 of an electrostatic unit, the energy acquired will be

$$W = eV = \frac{e}{30} = \frac{4{\cdot}77 \times 10^{-10}}{30} = 1{\cdot}26 \times 10^{-11} \text{ ergs.}$$

The velocity corresponding to this energy, for a mass so small as an electron, is the square root of $2W/m$, or $\sqrt{\left(\frac{2}{m}\cdot\frac{e}{30}\right)} = 1{\cdot}88 \times 10^8$ centims. per second.

If the drop of potential, instead of being 10 volts, were 1000 volts, the energy would be a hundred times as great; but the velocity would be only ten times as great. To get up a velocity of $1{\cdot}88 \times 10^{10}$ cm. per sec. would require a potential-difference of 100,000 volts.

But now that we are getting within hail of the velocity of light, matters are complicated by the increase of mass experienced by such high speed electrons; and the simple law fails to hold.

Ionisation Potential

Still, it will be interesting to reckon the ionisation potential corresponding to the fundamental ionisation energy *Bh*.

It is simply Bh/e; while the corresponding ionisation velocity, or the speed with which an electron is propelled by this difference of potentials, is $\sqrt{\left(\frac{Bh}{e}\cdot\frac{2e}{m}\right)}$. To reckon Bh/e we have only to use the figures recorded on page 174;

$$\frac{Bh}{e} = \frac{2{\cdot}154 + 10^{-11}}{4{\cdot}77 \times 10^{-10}} \text{ electrostatic units.}$$

To convert these into volts we must multiply by 300. So the basic ionisation potential Bh/e is 13·5 volts. The corresponding speed may be reckoned as $2{\cdot}19 \times 10^8$ cm. per sec.; and it will be found to correspond with the expression for it above, viz.,

$$u = \sqrt{\left(2\frac{e}{m}V\right)} = \sqrt{\frac{2Bh}{m}}.$$

For any other hydrogen orbit than K, say the nth, the ionisation potential is $\frac{13{\cdot}5}{n^2}$ volts; while for the K orbit of any atom of atomic number N, it is $13{\cdot}5N^2$ volts.

So to get an electron away from the innermost orbit of a heavy element must need a very high potential, comparable with 120,000 volts.

If there were no trouble about increased mass, the potential of 280,000 volts would generate in an electron the speed of light; but the inevitable increase of inertia makes the final stages in the attainment of such a speed impossible.

Effects near a Nucleus

It is worth noticing that close up to a nucleus the potential is very great, being represented by Ne/a for an atom of number N; where a, the radius of the nucleus, is of the order 10^{-12} centimetre. For a heavy atom, of number $N = 90$, this potential would be comparable with 43,000 E.S. units, or 13 million volts; and such a potential as that would be sufficient to confer great speed even on an alpha-particle or helium nucleus, although it is 4×1850 times as massive as an electron.

To reckon the maximum speed which might possibly be attained by an ejected alpha particle, supposing it had a double positive charge, while escaping from actual contact with a highly charged positive nucleus, like that of, say, radium, we could reckon $u = \sqrt{\left(2 \cdot \frac{2e}{4M} V\right)}$, with M the mass of a proton, or $1{\cdot}66 \times 10^{-24}$ gram.

The value of u, so reckoned, comes out as $3\frac{1}{2}$ times 10^9 centim. per second, which is about twice what is actually measured at a little distance away. This may look as if the helium particle was not doubly ionised when ejected—or as if it had only lost one of its neutralising electrons—but the mechanism of ejection is not properly known at present—it may be retarded by the attraction of the crowd of electrons it has to penetrate—and all we need notice now is the competence of electrostatic potential to achieve the disruption, if properly stimulated. Indeed, the wonder is that the nucleus of an atom holds together at all, under the enormous disruptive forces. There must be compensation and adequate stability somehow.

Simple Practical Rule for Converting Voltage-Drop into Actual Speeds

From the general expression $u = \sqrt{\left(2\frac{e}{m}V\right)}$ or $\frac{1}{2}mu^2 = eV$, it is plain that velocity acquired by falling down a certain step of potential is proportional to the square root of that step. A table is sometimes constructed enabling us to pick out the velocity u corresponding to a given potential difference V, or *vice versa*; but the following simple formulæ may suffice, and are accurate enough for all ordinary purposes :—

For an electron falling down any known voltage, when the speed is not excessive so as to increase its mass appreciably,	$u = 6 \times 10^7 \sqrt{\text{volts}}$, in centimetres per sec.
For an alpha-particle, or helium nucleus with double charge, and with its normal mass 4×1850 times that of an electron,	$u = 10^6 \sqrt{\text{volts}}$, in centimetres per sec.

So even a 1-volt drop generates a considerable speed; 600 kilometres or 400 miles a second in the first case, and 10 kilometres or roughly 7 miles a second in the other.

The wave-length of radiation corresponding to any given drop of voltage can be reckoned thus, $\lambda = \frac{12400}{\text{volts}}$, the wave-length being specified in Angstrom units, each of which is 10^{-8} centimetre (the ordinary atomic dimension).

CHAPTER XXI

NUMERICAL VALUES FOR DETAILS OF ATOMIC STRUCTURE

It is not essential to the argument, but it is interesting to reckon the absolute numerical value of the quantities belonging to an electron when it is revolving in one of the intra-atomic orbits. We have got the algebraical expressions for them, and we have only to interpret them numerically, in terms of certain standard constants metrically and independently determined in a laboratory.

Different observers have got slightly different results for these important constants, but there is a consensus among all experimenters as to their order of magnitude, which is the chief feature of interest, and of late years the actual measurements have tended more and more to close agreement. Perhaps the most precise and exact of the laboratory determinations have been those of Professor Millikan, while working in that splendid physical laboratory attached to the University of Chicago, where, as in other American Institutions, owing to the liberality of munificent donors, experimental facilities of all kinds abound.

Measurements have been made by many independent observers and were obtained by methods quite distinct from spectrum determinations; except, of course, the Balmer constant. To explain how the results are got would take too long, but we may cite the results. (See Table I.)

If we obtain the theoretical value of B by using the other data and calculating it from the dynamical equation for the case of hydrogen, as

$$B = \frac{me^4}{4\pi A^3}$$

we get $\qquad B = 3{\cdot}27 \times 10^{15}$ per second

or $\qquad B/c = 1{\cdot}09 \times 10^5$ per centimetre,

which correspond closely with the spectrum measurements cited in the table just above, although in the calculation there are no sort of data derived from spectra of any kind, and although tremendous powers of 10 are involved; so that the discrepancy might have mounted to millions or trillions, if the application of regular orbital theory had not been right.

This represents Bohr's really splendid initial achievement, referred to near the end of Chapter XIX.

TABLE I.—LIST OF FUNDAMENTAL CONSTANTS, AS MEASURED.

Charge of an electron,	$e = 4{\cdot}774 \times 10^{-10}$ electrostatic c.g.s. units; (only the last figure being quite uncertain).
Mass of a hydrogen atom,	$M = 1{\cdot}662 \times 10^{-24}$ gramme.
Mass of an electron,	$m = 0{\cdot}9 \times 10^{-27}$ gramme.
Hence,	$M/m = 1845$ or something between 1840 and 1850.
Planck's constant, or quantum unit,	$h = 6{\cdot}547 \times 10^{-27}$ c.g.s. units; where the last two figures are rather uncertain. (Sometimes it is quoted as 6·56.)
Consequently the indivisible unit of angular momentum,	$A = \frac{h}{2\pi} = 1{\cdot}04 \times 10^{-27}$ of the same units.
While the Balmer frequency constant, or inverse wave-length constant, by spectrum measurement, is,	$B = 3{\cdot}29 \times 10^{15}$ per second.
or,	$B/c = 1{\cdot}09675 \times 10^{5}$ per centimetre of wave-length.

Calculation of Innermost Orbital Data from these Constants

Now of all the possible orbits the most stable and imperturbable of all is the innermost or K orbit, for which $n = 1$; this is the one which is likeliest to occur in atoms of all the elements, and in hydrogen is the one most frequently occupied by an electron. So putting the above values of the constant into the expression for this innermost orbit, we get for the radius of the K orbit of hydrogen,

$$r = \frac{A^2}{e^2 m} = 5{\cdot}27 \times 10^{-9} \text{ centimetres.}$$

Or $1/N$th of this for the K orbit of any other element, where N is the number of the element in the chemical series. The recognised size of the normal hydrogen atom is just about the size of what comes out here for the size of its K orbit; showing that that is the position of the single planetary electron in the atom of ordinary hydrogen.

(The radius of the L orbit for hydrogen would be 4 times the above, and of the M orbit 9 times; which is a good deal larger than the normal recognised size of the hydrogen atom.)

For the speed of the electron circulating in the K orbit of hydrogen,

$$v = \frac{e^2}{A} = 2{\cdot}19 \times 10^8 \text{ centim. per sec.}$$

Or N times this for the K orbit of any other element.

So the angular momentum mvr, for a particle in this K orbit, is simply the unit,

$$A = 1{\cdot}04 \times 10^{-27} \text{ c.g.s.}$$

It is the same or nearly the same for the innermost orbits of all the elements, because the N cancels out from the product vr.

The frequency of revolution,

$$\frac{\omega}{2\pi} = \frac{v}{2\pi r} = \frac{me^4}{2\pi A^3} = 2B = 6{\cdot}6 \times 10^{15} \text{ per sec.}$$

or N^2 times this for other elements.

As to the kinetic energy of the revolving particle, that is easily reckoned :—

$$W = \tfrac{1}{2}mv^2 = \frac{me^4}{2A^2} = 2\pi AB = Bh = 2{\cdot}154 \times 10^{-11} \text{ ergs.}$$

Or, again, N^2 times this for the K orbit of other elements.

We cannot specify the radiative frequency or wave-length as characteristic of any particular orbit, for radiation is only emitted when a particle drops into an orbit; and the surplusage of energy of the particle—the energy which has to be emitted—will depend upon whence it came. If the particle has come from infinity we can readily specify the frequency of what it will radiate on dropping into the inner or K orbit, for it will be simply equal to the Balmer constant B; that is to say,

$$\text{the } K \text{ ionisation frequency} = \frac{me^4}{4\pi A^3} = B = 3\cdot3 \times 10^{15} \text{ per sec.}$$

And for any other element it will be N^2 times this. So for Uranium it should be something like

$$8464 \times 3\cdot3 \times 10^{15} = 2\cdot8 \times 10^{19}.$$

No frequency of incident radiation less than this would be able to eject an electron from the K orbit of Uranium.

The ionisation frequency, B or N^2B, constitutes the highest line or head of the K series of lines. The other lines are given by particles starting from other orbits, and these other lines are not far away. The line belonging to a particle coming from the next adjacent orbit No. 2, will, for instance, be characterised by the frequency $B\left(\frac{1}{1} - \frac{1}{4}\right)$ or $\frac{3}{4}B$; and that will be the lowest or, so to speak, reddest line of the K series.

To deal with other orbits simply an atom must be ionised, so as to remove perturbing electrons. By the use of a hot spark Professor Millikan finds that many atoms can be more or less thoroughly ionised; and if an atom is thus reduced to an earth-moon system, even though it has a powerful N-fold nucleus, the single satellite will obey Bohr's laws accurately, and is likely to give a series of lines in the ultra-violet or X-ray spectrum characterised by a Balmer constant $(N-2)^2B$; because all atoms cling to the two inner revolving electrons very tightly, although most or all of the others can be peeled off or jerked momentarily away.

CHAPTER XXII

COMMENT ON THE ABOVE NUMBERS

1*st*, *Speed*. Taking first the speed with which the electron is circulating in the innermost orbit of hydrogen, we see that though it is an enormous speed—about 2,000 kilometres, or 1,300 miles, per second—yet that it is far below the velocity of light. But when we reckon the speed for one of the heavier atoms, with a much more highly charged nucleus—taking the extreme case of uranium, for instance, the value of whose atomic number N is 92—we see that the speed of the innermost or K electron in that case is 2×10^{10} centimetres a second, or 2/3rds of the speed of light; while anything circulating inside that orbit—if there is anything—would have a still higher speed. But any velocity approaching that of light introduces curious consequences.

It was known long ago, before the theory of Relativity was mooted, that the mass of bodies became theoretically infinite at the velocity of light, and increased very rapidly as that speed was approached. This was an immediate consequence of the electrical theory of matter. The mass of a body at speed v is its ordinary slow mass multiplied by $\frac{c}{\sqrt{(c^2 - v^2)}}$; where c is the limiting velocity possible in ether, which is known as the velocity of light. For a speed 2/3rds of c, the factor becomes $3/\sqrt{5}$, which is about $\frac{4}{3}$. Hence the mass of an electron moving at that speed is 4/3rds of its ordinary mass; and every little increase of speed beyond that runs the mass up prodigiously. Hence no wonder that there is an instability in these atoms, and that they are liable to fly to pieces under the action of some unknown stimulus. I pointed out long ago (see *Nature* for June 11, 1903, vol. 68, p. 128), that this increase of mass was likely to result in instability whenever the internal movements in an atom reached a high enough figure. This paper is still worth referring to, I am glad to find.

The actual mechanism of atomic explosion is at present concealed, and it is clear that such explosion only happens occasionally. It may be that for still heavier atoms disruption occurs very frequently; and accordingly atoms much heavier than uranium are either non-existent or rare. They tend to split up, somewhat as stars which are too massive are liable to split up; though the reasons are different.

Although the speed of the inner hydrogen electron does not attain 1 per cent. of the velocity of light, yet the increase of mass for even that speed is by no means negligible; and it has important consequences.

The speed even of the planet Mercury, which is the six-thousandth part of the speed of light, is not altogether negligible in this respect; and inasmuch as the orbit is elliptical, so that the speed varies at different points, an astronomical result is produced which can be calculated. (See my Papers in the *Philosophical Magazine* for August, 1917, and February, 1918; especially the $\frac{1}{2}\alpha^2\theta$ term on p. 149.) The result is that the orbit revolves in its own plane, the apses or extremities of the major axis gradually moving forward by 1/6th of the Einstein value. To get the full astronomical value, the solar system must travel through the ether at a definite pace in a definite direction. But that introduces trouble with other inner planets. The effect of the actual solar motion, whatever it is, appears to be compensated by an unexpected and otherwise unknown modification in the gravitation constant; as Prof. Eddington agrees.

The rotation of an orbit behaves as if the revolving body were affected by a double movement, two revolutions in opposite directions nearly of the same period. And if it were revolving fast enough to give anything comparable to a spectrum line, that line would be doubled by the combination of frequencies into which the revolving orbit can be analysed. Though that is an absurd mode of expression in connection with the planet Mercury, it is a nearly accurate mode of expression for the electron. For in so far as this revolution frequency gives anything analysable in the spectroscope, the increased mass due to speed will, as it were, superpose upon that frequency another nearly equal one. And accordingly the line will be doubled.

This gives some idea of the general principle on which Prof. Sommerfeld of Munich has analysed the *X*-ray spectrum lines—which are generated by very high speeds—and has shown that in consequence of this variation of mass with speed they will not be simple but multiple lines. He thus brilliantly accounted for the fine structure of these lines which has actually been observed.

2nd, Size of Orbit. If we now proceed to attend to the radius of the innermost orbit, we find for hydrogen something like the radius of the atom itself; the diameter of the orbit coming out about 10^{-8} centim. (see above). This result alone was interesting and encouraging when first realised. For uranium the innermost orbit comes out very much smaller; 1/92nd of that size. And yet even that small orbit is much bigger than what is commonly considered the size of the nucleus; which is a hundred times smaller still. Hence any protuberance on that nucleus—say a slightly dislodged portion, such as a charged helium atom—will have to revolve at a still greater speed. And accordingly it cannot possibly be stable. At the moment of explosion the mass of the violently moving portion *might* approximate to all the rest of the nucleus; though immediately it has escaped and become an alpha-particle, so that its speed can be measured, it is found to be moving at a more reasonable, though still very high, velocity, estimated as round about one-twentieth the speed of light, or sometimes as much as 12,000 miles a second.

We must have some compunction in pressing simple laws so near the confines of the nucleus; but if we do, we shall find that the speed of light is reached at a radius of

$4 \cdot 5 \times 10^{-12}$ centimetres from the centre of a uranium or radium nucleus. So that in that region we should certainly expect to find critical values attained; and indeed it suggests a size for the nucleus.

3*rd*, *Frequency of Revolution.* If we now attend to the frequencies of revolution, we see that in the *K* orbit of a hydrogen atom they are a good deal higher than corresponds to visible light, but that still they are of that order of magnitude, and therefore correspond to the frequencies in the ultra-violet part of the spectrum. In the *L* orbit of hydrogen the frequency corresponds to that of visible light. But the frequency runs up to extreme values for the heavier atoms, increasing as the square of the atomic number; and therefore, as the chemical series is ascended, it very soon gets into the region of *X*-rays. Consequently even moderately heavy atoms cannot be ionised or dissociated by visible illumination, but can be disturbed by *X*-ray frequencies; the frequency needed to ionise an oxygen atom, for instance, should be sixty-four times that which is sufficient to ionise hydrogen.

Of course some of the outlying electrons—if there are any—can be flung off by lower rates of vibration. But the theory of the outer orbits of heavy atoms is, as we shall find by study, rather complicated, and has not yet been worked out with any sort of completeness. It is only for the innermost orbit that we can attempt to apply the simple theory. And even there, conditions are likely to be complicated by the probability that in most atoms, a pair of electrons are circulating in that inner orbit, and presumably repelling each other; to that extent furnishing a radial component which tends to diminish the central attraction.

It must suffice, here and now, to indicate the difficulties which confront us when applying Bohr's theory to heavy atoms. It only applies in its simplicity to hydrogen and ionised helium, and requires supplementing before other atoms can be rationally dealt with, except in a roughly approximate manner. Many others are working at these more difficult problems, including Bohr himself; and in a few years' time we may expect our knowledge to be surprisingly increased, now that the clue has been put into our hands.

CHAPTER XXIII

ATTEMPT TO GENERALISE FOR OTHER ATOMS

THE primary theory only enables us to deal fully with a primary atom like the simple atom of hydrogen, but a great deal of the theory applies with modification to other and more complex atoms; though when the atoms get really complex, a number of other considerations have to be taken into account, and some new phenomena make their appearance. Notably radioactivity, or the explosion and breaking up of the nucleus: but other things too, more subtle than that.

The hydrogen atom consists of a proton and an electron revolving in one or other of the possible orbits. The next most simple atom is that of helium, of atomic weight 4 (or nearly four times that of hydrogen), whose nucleus is a close-packed group of four protons held together apparently by two bound or constitutional electrons; and this nucleus is well known as existing separately for a time as the alpha-particle ejected violently from radium.

It is not neutral, of course, any more than the hydrogen nucleus is neutral; it has two unbalanced positive charges, and may be said to consist of two neutralised protons and two active protons, all compactly welded together into an exceedingly stable aggregate. It is able, therefore, to sustain in revolution two extra electrons, which convert the alpha-particle into the neutral and satisfied atom of helium. Such atoms are so satisfied that they do not even combine in pairs; they continue monatomic.

Applying dynamics to a single satellite electron revolving round this helium nucleus, we perceive that we have a sort of earth-moon system to deal with, whose charge and attracting force is double, and whose central mass is quadruple, what they were for hydrogen. So when we come to interpret the usual centrifugal force equation, which written *fully* is

$$\frac{mv^2}{r} \cdot \frac{M}{M+m} = \frac{Ee}{Kr^2},$$

we must remember that for helium the E is doubled and the M is quadrupled. The K we can ignore for all practical purposes; but theoretically it is well to remember that electrical and material quantities cannot be equated, unless *two* essentially unknown quantities are present, so as to cancel from each other's unknown portion the part which is common to both.

(Parenthetically, in case an Electrician jibs at this cryptic but quite true pronouncement, he may bethink himself of RI^2t, $\frac{1}{2}LI^2$, eV, $\frac{1}{2}CV^2$, all which involve two electric quantities and therefore can be equated to mechanical energy; and again of LC, L/R, RC, all which can be interpreted in terms of time. But no mechanical interpretation can be given to e^2 or R or C or V or L or I separately, unless an electric or magnetic factor such as K or μ is introduced too.) To return to our proper subject :—

The doubling of E is so important that we had better express it clearly as $2e$, 2 being Moseley's atomic number for helium, as the second member in the atomic series. In general the atomic number is N, and the nuclear charge is $E = Ne$; whereas for hydrogen $E = e$ simply.

Accordingly, ignoring for the present the small correction factor $\frac{M}{M + m}$, which becomes less and less important as the mass of the nucleus is increased, but which is not altogether negligible in the case of hydrogen (as we shall see), we may write,

$$rv^2 = \frac{Ne^2}{m},$$

for any atom whose atomic number is N. And so the main outline of theory remains the same for heavier atoms, subject to important corrections and supplements, except that Ne must be written for E in all the results. Hence whenever E or E^2 occurs in a formula, the factor N or N^2 will introduce itself into the numerical interpretation.

The permissible orbits are still regulated by the atomicity or quantification of angular momentum or rate of sweeping areas; and, so far as any are circles, their radii still proceed outwards from the nucleus as the squares of the natural numbers. Hence, as a first idea we might conjecture that

$$r = \frac{n^2h^2}{4\pi^2 mNe^2}$$

$$v = \frac{2\pi Ne^2}{nh}$$

$$\omega = \frac{8\pi^3 mN^2e^4}{n^3h^3}$$

$$W_1 - W_2 = \frac{2\pi^2 mN^2e^4}{h^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

$$\nu = \frac{2\pi^2 mN^2e^4}{h^3}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

for all atoms whatever. The constant factor outside the last bracket being N^2B; which is the appropriate generalised Balmer constant.

The lines of the helium spectra are therefore to be expected at positions in the frequency scale determined by

$$4B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

if B has the same value as before. For it will now be multiplied by the factor 2^2.

And for any other element we might expect its simplest spectrum line series to be given by

$$N^2B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

where n_1 and n_2 are simple integers as usual.

Caution

But now it must be clearly admitted that when dealing with a really complex atom the simple centrifugal force equation will not apply; certainly not to its outer orbits. For the attraction of the nucleus is by no means the only force acting there. The attracting force of the centre is largely masked, for an outer orbit, by the crowd of electrons circulating in the inner orbits, all which will contribute their repelling force. Consequently for a single electron in the very outermost orbit we shall have very nearly the same net attraction as we had in the case of hydrogen; because all but one of the active nuclear protons will have their activity balanced by the set of neutralising planetary electrons. Electrons outside any orbit under consideration may be ignored, but those inside any orbit are quite effective. Only, as they are in rapid motion, and distributed non-uniformly as spots on circles, it is not so easy to specify their force accurately, as it was for the central nucleus. Mathematics—trigonometry at least—would have to be introduced. Suffice it therefore to say here, roughly and approximately, that for the outermost orbit of all we may take the unneutralised charge of the attracting centre, as nearly e, on the average; only that it will be complicated by a curious periodicity or sinuosity, owing to the changing positions of the inner orbital electrons. See, however, the paragraph concluding Chap. XXI, page 176, for a hint at other possibilities.

The full treatment, as now in process of developing in the hands of physicists of many countries, is not yet quite appropriate to an elementary book. It will be more profitable to call attention to the rather dramatic episode of the helium spectrum.

CHAPTER XXIV

HISTORY OF THE HELIUM SPECTRUM

When helium lines were first measured, some of them were thought to be due to hydrogen, and were thought to make an exception to the usual simple Balmer or Ritz or Rydberg rule, inasmuch as fractions appeared in the numerical portion instead of whole numbers. The history of this apparent anomaly is rather interesting.

Professor Pickering, in America, observing the spectra of some of the stars, found, in addition to the orthodox hydrogen spectrum series, another series of lines expressible thus

$$\nu = B\left(\frac{1}{4} - \frac{1}{(n+\frac{1}{2})^2}\right),$$

which is very like the old Balmer formula except that $n + \frac{1}{2}$ is manifestly not an integer. This series of apparently hydrogen lines, which were accurately represented by this expression, accordingly became famous as the Pickering series. Then, a little later, Rydberg discovered, also in the stars, another new series, expressible with accuracy thus,

$$B\left(\frac{1}{(3/2)^2} - \frac{1}{n^2}\right),$$

where again a fraction appears instead of one of the integers.

So far, it seemed impossible to get these lines in the laboratory; but Professor Fowler of South Kensington, by passing a very powerful discharge through a mixture of hydrogen and helium, succeeded in getting both the Pickering and Rydberg series in the laboratory; and he also got another, or Fowler series, expressible as

$$B\left(\frac{1}{(3/2)^2} - \frac{1}{(n+\frac{1}{2})^2}\right),$$

which combined the peculiarities of both the other series, by having fractions in place of *both* the integers.

If these lines had been really due to hydrogen, as was then almost universally supposed, it would have been rather a blow to Bohr's application of quantum considerations to determine the permissible atomic orbits, whose radii had to proceed as n^2 with n an integer. It began now to look as if intermediate orbits were, under exceptional conditions, possible. Bohr, however, triumphantly attacked the problem. He knew that the frequency expression for a helium spectrum ought to have the ordinary Balmer constant B multiplied by 4; that is, by N^2: as we have said above. So instead of allowing fractions in the numerical part of the formula—where the $\frac{1}{N}$, or in this case $\frac{1}{2}$, occurs—the $\frac{1}{2}$ which occurs in those denominators under the square index might equally well be extracted, inverted, and placed outside as part of the appropriate Balmer constant; and then all would come out right, under the orthodox expression,

$$4B\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right),$$

with n_1 and n_2 integers as usual.

Accordingly he assumed that these odd and interesting spectra were not due to hydrogen, but to helium. And yet they had never been seen in the regular spectrum of pure helium! Why not? He replied, because to get these spectra the helium atom must be half ionised, and one of its planetary electrons removed, so as to leave the other under the full attraction of the doubly charged nucleus; and that probably the ionisation was effected by a foreign ingredient.

The explanation was, in the main, accepted; and the admixture with hydrogen which appeared necessary for the production of these spectra—whether in a star or in a laboratory—was held responsible for the necessary semi-ionisation, probably by reason of molecular encounters or collisions, with occasional transfer of constituents.

If, in the last formula, n_1 is put equal to 3, and n_2 successively equal to 4, 5, 6, 7, etc., the Rydberg and Fowler series come out, with the use of the quadruple B; the even numbers giving one, the odd numbers the other. While if, still using this multiple B, we put $n_1 = 4$, with n_2 equal to 5, 7, 9, 11, etc., we get the Pickering series coming out too, not as a variety of the second series of hydrogen, as had appeared likely, but as part of a normal fourth series of ionised helium.

The even values for n_2, such as 6, 8, 10, etc., give the other part of the same fourth helium series; but this part is exactly coincident with the regular Balmer series for hydrogen. So no wonder it was mistaken for it! Especially as some hydrogen has to be present, and no doubt does contribute to make this even-number portion more conspicuous than the odd-number portion; which, as Bohr said, must belong wholly to helium.

This view of the matter was soon clinched by the following delicate point: a case of the apparent exception proving the rule. Exact measurements, by Fowler, of the absolute values of the wave-lengths of the spectral lines, made the observed series agree with Bohr's helium theory very nearly, but not quite up to the limits of modern spectroscopic accuracy. The general succession was all right, but there was a discrepancy in absolute value, of 4 parts in ten thousand; expressible by finding as the necessary conversion factor not exactly 4 but 4·0016.

The fourth helium even-number series last mentioned above, for instance, which ought apparently to coincide precisely with the second hydrogen or Balmer series, could not have fitted exactly. They would differ as if the factor outside the brackets, for the case of helium, were $4{\cdot}0016B$ instead of $4B$. In other words, the factor as observationally measured was not exactly 2^2, as theory seemed to indicate, but a trifle greater.

Why did the theory not give the right factor? Bohr was able immediately to say that it did, as soon as the theory was made complete and was not left only approximate. In the reckoning of 4 we have left out the little correction which we know has to be applied, in strictness, to m the electronic mass, because it is revolving, not round a stationary nucleus, but round a common centre of inertia; namely, the factor $\frac{M}{M+m}$ (see pp. 161 and 164). For in the case of helium this correction factor will be slightly different, it will become $\frac{4M}{4M+m}$; where M is the mass of a proton, which is 1850 m. Consequently the 4 (in the coefficient whereby the helium and hydrogen constants differ) will, in the full theory, be not exactly 4, but 4 multiplied by the following fraction

$$\frac{4M}{4M+m} \div \frac{M}{M+m};$$

that is to say, by the ratio of the helium correction factor to the hydrogen correction factor.

Doing the arithmetic, the theoretical factor comes out not exactly 4, but

$$4 \times \frac{4(M+m)}{4M+m} = 4 + \frac{3}{1850} = 4{\cdot}00162.$$

Whereas spectroscopic observation and careful measurement had made the discrepancy 4·0016. The numbers are identical! The explanation is complete.

CHAPTER XXV

THE RELATIONS BETWEEN MATTER, ENERGY, AND ETHER

Having thus dealt with the more elementary and best known and most fully established recently discovered relations between the atom of matter and its radiation,—in other words, with the beginning of the interaction between Electricity and Ether,—it has become manifest that in order to make anything like a comprehensive and satisfactory theory, a great deal more must be known about the properties of the Ether of Space and the constitution of the electron,—and incidentally of the positive electron or proton also,—than we know at present. Nevertheless, even already much has become known in a general way, chiefly through the Theory of Relativity in some of its various and tentative aspects. But to expound this and other developments, some achieved and some anticipated, will require, not another chapter mainly on the Ether, but another volume.

A beginning has also been made—indeed more than a beginning—of the application of Bohr's Theory to many of the chemical types of atom; whereby a growing attempt is being made to explain the properties of the chemical elements in terms of the electrical constitution of their more complex atoms. Not only indeed has atomic constitution been attacked in this way, but a beginning has been made of the treatment of molecular constitution also, that is to say, a study of the way in which atoms combine into molecules, and the anticipated properties of those molecules. All this latter part must be of high chemical interest; but it needs a great deal of further elaboration before it is adapted to anything like popular exposition.

Leaving aside the more purely chemical developments, there remains a good deal that has been ascertained about the relations between matter, energy, and ether. And some indication of the results may fittingly conclude this book.

Nature of Mass

In the Newtonian and Galilean scheme of dynamics—which has been responsible for all the advances in mathematical and general physics throughout the past few centuries—the idea of mass or inertia has been a fundamental notion, incapable of explanation or reduction to anything simpler. It has been one of the fundamental data which had to be granted, and the mass of bodies had to be assumed constant; the accepted doctrine being that called the Conservation of Matter.

The characteristic property of all " matter " is locomotion. It possesses this property without let or hindrance, by its own nature, in accordance with Newton's First Law, the law of inertia; namely, that motion is rectilinear and uniform except in so far as it is accelerated by external force.

" Force " constituted the second fundamental idea in the Newtonian system, and the law of force is expressed in Newton's Second Law; namely, that the acceleration produced by it is proportional to the acting or " resultant " force. In other words, that the inertia of a given portion or quantity of matter, measured by the ratio of force to acceleration, is constant.

The Third Law gives the Conservation of Momentum; which Newton expressed by saying that action and reaction are equal and opposite. Or in other words, that wherever there was one force propelling a body, there was also an equal opposite force acting on the body which propelled it; so that on the whole the quantity of motion or momentum generated was zero, one of the bodies gaining what the other body lost. This can be illustrated by innumerable examples, such as the recoil of guns when firing a projectile, or, more simply, by the explosion of a shell in mid air; for the centre of gravity of the shell continues its parabolic path totally unaffected by the internal disturbance, however violent, so long as no external force acts. Hence, whatever momentum the shell possessed before the explosion, it possesses the same after; and the centre of gravity of the shrapnel, or other parts into which it is sub-divided, continues in its unaltered course; for though additional motions are conferred upon the parts by reason of the explosive energy, the aggregate momentum of those additional motions is zero,—that is to say, as much forward as backward, as much to the right as to the left, and as much up as down.

Nature of Energy

The term " energy " is of comparatively recent introduction, and represents the work that can be done by forces acting on matter. And Newton's Third Law, combined with the denial of action at a distance, can be held to establish the Conservation of Energy,—a great generalisation which took its rise in the middle of the 19th century, having been established mainly by the work of Joule; for before his time, though it was known that energy was conserved in machines in a certain sense,—no more being ever obtainable from them than was put into them, which is the denial of the possibility of what used to be sought as Perpetual Motion—it was thought that, though energy could never be generated, it might be lost or destroyed, by friction, imperfect elasticity, and other dissipating causes, which only resulted in heat, or possibly heat and noise. But Joule collected all these accidental or subsidiary by-products, and showed that when they were properly measured they accounted for all the lost energy, and that if they were included among the forms of energy, the total energy was constant, not being capable of either increase or diminution by any process known to man.

Thus we appeared to have a complete and satisfactory system of Physics, dominated by the Conservation of Mass, the Conservation of Momentum, and the Conservation of

Energy; the latter being observed and measured in a protean multitude of forms. The very same energy might take the form of sound, light, heat, electric charge, electric currents, raised weights, bent springs, moving and spinning bodies, and radiation generally,—in fact, in all the known varieties of motion and strain in both matter and ether.

But then, towards the end of the century, it was found that radiation strangely simulated some of the properties of matter. It exerted a minute pressure on bodies receiving it, exactly as if it possessed momentum. Hence it appeared as if radiation was itself a form of matter, a peculiar and restricted and temporary form, which necessarily travelled with the velocity of light; whereas ordinary forms of matter seemed able to travel at any speed appropriate to the conditions of an observer.

It had to be admitted, however, that all these observed motions, except that of light, were relative, and that we had no means of ascertaining what the absolute motion of any piece of matter was. What we called " kinetic energy " was the energy of motion with reference to the earth. The earth was known to be moving round the sun, but that motion was usually ignored. The sun was known to be moving with reference to the stars; and what the stars were doing was not known. Absolute motion, therefore, seemed inaccessible, and perhaps meaningless, for matter; and we had to be content to concentrate our attention on operations in a limited self-contained system, in which the Newtonian laws seemed accurately obeyed.

Matter and Energy

The only forces observable being due to the interaction of the parts of such a system, and the forces being always a pair with equal opposite components, they came to be called " a stress," and the word " force " grew rather into disrepute. Still Newton's Laws seemed to hold the field. But the peculiar behaviour of radiation, combined with

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Newton's Third Law, suggested that the barrier or distinction between matter and energy was showing signs of weakness, and exhibiting a tendency to break down. The Electrical Theory of Matter emphasised the lack of distinction between matter and energy, and began to suggest that after all they might be different aspects of one thing. Or in other words, that to the already numerous forms which energy might take, the familiar form which we had called "matter" must be added. It began to be realised that Matter must no longer be thought of as something distinct and totally different in character from energy: it may differ from the other forms of energy no more than heat differs from electric charge, or these from a wound-up spring or gunpowder, or again from a flying bullet or an electric current. For it was found that the energy in the electrostatic field of an electron was equivalent to what had been called previously the "mass" of the electron. Now an electrostatic field certainly exists in the ether. An electric field, apart from its central nucleus or charge, certainly appeals to us as energy and not as matter. And yet a combination of experiment and theory showed that an electron has no mass except the energy of its electric field. And inasmuch as all matter appeared to be composed of electrons, or at least of electric charges in some kind of grouping, it seemed likely that matter could wholly be accounted for in terms of etherial energy.

Then, however, it was perceived that if mass was dependent on energy it could not be constant; it must depend to some extent upon motion. As long as an electron remains stationary, its mass is constant. But directly it begins to move at any considerable speed, a magnetic field is superadded, and thus its energy and mass increases. The law of increase could be calculated; it was calculated, both by J. J. Thomson and Oliver Heaviside, and was subsequently verified by experiment! This dealt a blow at Newton's First and Second Laws: or, as we should prefer to express it, supplemented and corrected them in a profoundly interesting manner. So much so that to this day the only law of Newton's which appears to hold the field unchanged is the Third Law, that action and reaction are equal and opposite.

Introduction of an Absolute Velocity

Then came the Theory of Relativity, and completed the downfall of the barrier between matter and energy. It also emphasised in a remarkable manner the fundamental importance of a certain velocity, a critical and unchangeable velocity, an absolute universal constant, which evidently represents something constitutional in the ether; which can be fairly or provisionally measured experimentally, by ascertaining the rate at which the ether transmits waves. It may be safely assumed that this fundamental constitutional velocity of the universe is unchangeable by any experiment. And this the Theory of Relativity boldly stated, in more questionable form, by saying that the velocity of light in free space was not only itself an absolute constant, but must appear the same to every observer: in fact, that it too was unchangeable by any experiment, and must appear unchangeable to any experimenter. The statement in this form, though still essentially of the nature of a postulate, was supported by the negative evidence that no experiment yet made—and many had been tried—had succeeded in demonstrating any modification of the measured velocity of light in free space. And that is the position to-day.

Absolute Energy

The Theory of Relativity used this fundamental unchangeable velocity in a remarkable way, to exhibit the actual relation between matter and other forms of energy. It conferred an intrinsic and absolute amount of energy on all matter, in amount the same as if it were moving with the velocity of light. Or conversely, it conferred inertia upon all energy, the amount of inertia being the energy divided by the square of the velocity of light. And this was asserted to be true, no matter what the form of energy, or what the form of matter, was. The two were in a manner identified, the ratio between them being c^2.

If this is true—and there is no reason to doubt it,—the meaning must be something portentous. To my mind it means that the ether has a constitutional whirling motion, like an exceedingly fine-grained vortex motion, circulating with this velocity c; while certain portions of the ether are modified into what we know as electrons and protons, which build up all the forms of matter. That all this needs much more explanation to make it intelligible, except to physicists, is fully understood; but the subject is too large for any but the merest summary in the present volume. Moreover, it needs elaboration by mathematicians. So I go on to say—with some confidence,—concerning the rotational ether of which portions have somehow been modified into the elementary ingredients of matter,—that the amount of this modified ether is capable of variation, though the circulatory speed is invariable; and that all the activities we experience in the material universe are due to fluctuations in the amount of modified ether. When the amount increases, even a little, we call it locomotion, or some other form of energy. It is as if a slight translational motion was superimposed on the rotatory motion; or as if slightly more than usual of the normal ether were converted into matter; and accordingly not only is the mass variable, but all the phenomena in the visible and sensible universe are due to its variation. Observed energy does not appeal to us, or display itself to us, as variation of mass; even though that is what it really is; it appeals to us in innumerable other ways,—as the flying of bullets, the motion of railway trains, as solids, liquids, and gases, as music, light, and colour,—and every other of the familiar phenomena of our daily life, including our own bodies.

CHAPTER XXVI

POSSIBLE APPLICATIONS IN THE FUTURE

VERY well, that being so, and whether we are prepared to accept it or not we can at least use it as a working hypothesis, there must be some application not yet realised of so portentous and remarkable an idea. The amount of energy stored in the ether is enormous, and even the small fraction of it stored in matter is very great: far greater than any energy with which we have yet had to deal. The energy of combustion, of chemical action and explosives, and the energies exhibited by flying masses of matter, are insignificant compared with the intrinsic energy of matter itself,—its energy of atomic constitution;—of which a great part is permanently embedded in the electric fields surrounding the multitude of electrons. And this constitutional energy of matter is itself small compared with the constitutional energy of the unmodified or unelectrified ether; of which it appears to be a subordinate fraction.

When part of the hidden circulation of the ether is opened out into perceptible loops, we call it magnetism, and this is closely associated with locomotion. Locomotion is indeed part of the intrinsic and hidden energy becoming apparent. We see the energy, not only as matter, but also as moving matter. We can appreciate the energy of moving or circulatory ether apart from matter—for that we call magnetism—but we can also appreciate another modification of etherial energy as the locomotion of matter.

The question will more and more force itself upon our attention, Does the new knowledge, indefinite as it is at present, hold out any hope of making some part of this energy available to man? Is it accessible? Is there any mode of getting at it and utilising it? The idea is coming to the front that some of what we think of as the atomic energy of matter may be somehow made available. It is thought that this intrinsic energy is already being used to maintain the heat of the sun and other stars, though it is not yet tractable by any human device. It seems just possible that we may arrive at tapping the energy of the ether before we have learned to use the intrinsic energy of matter. Or probably we shall realise that there is no essential distinction between them, and that what we might call matter-energy really belongs to the ether; as every electric field does, and every magnetic field too.

We know that energy can take the form of locomotion; and by ingenious devices, such as those of James Watt, Stephenson, and others, we have learnt how to convert the unlikely energy of combustion into locomotion. Why should we not convert some of the intrinsic or atomic energy of matter into locomotion? If we could get at only 1 per cent. of it, we should have a prodigious source of energy. A vehicle which could dissipate some part of its own material at its tail might thereby be self-propelled by a sort of reaction on the ether; which, being of prodigious density, would itself hardly be disturbed, though undoubtedly it would be affected with an equal opposite momentum.

Some analogy to this kind of propulsion can be realised by thinking of a rocket, which, by expelling part of its material at a high speed through a throttle, projects itself in the opposite direction with a fair amount of energy. Well, I can imagine a rocket of the future, of no mean bulk, propelling itself at great speed by the disintegration or dematerialisation of an almost imperceptible portion of its own substance; thus converting what had been unknown or inaccessible energy into the energy of material locomotion.

Another analogy that might be suggested is a screw steamship. In the early days of the invention of the screw, it was considered remarkable—as indeed it is—that a great structure like a ship could be propelled by a small twirling mechanism at its stern. What the screw does is to drive the water backwards with equal opposite momentum; but as there is a great deal of water, the most obvious effect is the motion of the ship. If we could have the magnetic equivalent of a screw acting on the ether, even though it were only of microscopic size, the propulsion of a considerable mass of matter would be a natural consequence; for the ether is of tremendous density. A mode of propulsion like this would gradually replace every other source of energy, and make high speed aërial motion extremely easy. At present the propeller has to drive backwards the air, which is eight hundred times less massive than water, and accordingly there is a great blast and disturbance. Propulsion in water is easier; and if ever we learn to propel by means of ether, which is probably a billion times more massive than water, there will be no disturbance at all, but straightforward easy propulsion.

There used to be a comic elementary question, illustrative of a mechanical principle,—a student being asked,—How could a man get off a perfectly smooth large level table if he were placed in the middle of it out of reach of the edge? (The emphatic " perfectly smooth " precludes any possibility of walking or crawling.) The answer expected, but probably not received until after some thought, was that he could take something out of his pocket, throw it away, and await results; for he would then experience an equal opposite momentum, and therefore would slowly slide. If he were not allowed pockets, he would have to expectorate. The result would theoretically be the same.

This is the method adopted by rockets. Aeroplanes, steamships, and rowing-boats would be helpless in a perfect frictionless fluid. Water and air are not perfect fluids, they have some viscosity, consequently it is possible for the propeller to get hold of some of the surrounding medium and drive it backwards; the boat then goes forward with equal opposite momentum. A good deal of the surrounding medium has to be driven back, because its speed of propulsion is so moderate, and the density of its substance is moderate too. A dense fluid like mercury would to that extent be a more efficient medium. A rocket, however, could work in a vacuum, for it uses a portion of its own material; first converting it into hot gas, so that the small amount of material available can be ejected at a high velocity, with a momentum by no means negligible. But even so, the velocity with which gas can be expelled is only comparable to the speed of sound, which is a million times slower than light. Hence if any part of the substance could be ejected with the speed of light, the amount of substance required would be excessively small,—one-millionth of the amount ejected by a rocket to achieve the same result in the same time. A radioactive substance at the tail of a freely suspended body would therefore theoretically propel it by the reaction of its alpha-particles. And this reaction has been actually observed; for the alpha-particles are helium atoms ejected at a speed of, say, 12,000 miles a second as a maximum; which speed, though far below that of light, is getting into that neighbourhood.

But we might go further, and say that even a tail-light would theoretically do some propulsion; for radiation, as we know, possesses a minute amount of inertia and momentum, and really *is* emitted at the speed of light. The amount of matter ejected, even by the beam of a powerful searchlight, is so exceedingly small, however, that the reaction is practically imperceptible. Nevertheless it must be there; and accordingly anything emitting light in one direction must experience a minute force in the opposite direction.

Thus the general principle on which propulsion by etherial reaction may some day be accomplished is already known; and it only remains—though the remainder is a very large one—to find out some means of increasing its magnitude: in other words, some means of ejecting part of the material of a body at a speed near the velocity of light, in order to effect the propulsion of all the rest.

How soon locomotion of this kind may become feasible, no one can say. It would mean a great revolution in industry, for it would not be limited to what is ordinarily called locomotion, it could be used to drive machinery. But whether such a development comes soon or late, I fully expect that come it will; though let us hope not before both knowledge and wisdom have further increased, so that man's mind and will are sufficiently developed to refrain from using it for deleterious and deadly purposes.

Meanwhile, if anything ever does develop in this direction, it can be regarded as a surprising development of the early revolving arms driven by the wind from points. Few can have suspected, in the reaction-steam-jet of Hero of Alexandria, the germ of a ten-thousand horse-power Parson's steam turbine; and it is still more difficult to detect in the electric whirligig any foreshadowing of the power of the future.

CONCLUSION

Considerations such as those in the last two chapters belong more to a work on the Ether than to a book on Atoms and Rays, though the whole subject is so interlocked that discrimination is rather arbitrary. We have now expounded the general foundation for the electrical theory of matter, the general structure of the atom, and the remarkably full and accurate interpretation of spectroscopic results which have been already attained. Further developments are in process of incubation, some of the further discoveries already made we have hinted at; and now we can securely say that whatever modifications and complications may have to be introduced into the general theory of the atom, as time goes on, there can be no doubt that a first stride has been taken towards an understanding of its intimate structure.

The arithmetic at end of Chap. XXIV can be taken as an extremely simple example of the marvellously full and exact correspondence displayed between calculation and observation, which recent developments of the nuclear atom theory, and especially Bohr's detailed version of it, has rendered possible. Wherever calculation and measurement disagree, we see a hint for further examination and future discovery. How far the present theory may have to be modified in the future, we do not know; certainly it will have to be supplemented and enlarged; but that it contains a vital element of truth hardly anyone can doubt.

Exploration of the structure of the atom is a quite recent quest. Fifty years ago we did not suspect even that the atom had a structure. It seemed a hard, unbreakable, exactly-patterned geometrical solid, like "a manufactured article." Twenty-five years ago we doubted this, but still had no idea what the structure was. Now we analyse it into a regular group of points or specks, each having a definite small mass and an equally definite but great electric charge. These specks, of which the structure is not yet known, have great inter-spaces between them, and we apply to the motions of those specks, in the comparatively vast space inside the atom, the laws of astronomy; modified, it is true, by that at present mysterious limitation or condition—the quantum—about whose real meaning we are still in the dark. The brilliant attempts at further analysis of the atoms of all the chemical elements, so as to deduce their properties,—the full beauty of the atomic astronomy which is now unfolding before the eyes of enthusiastic experts—has been but little more than touched upon in this explanatory volume. We have dealt with the most secure and salient features. Further developments of the theory are at present too complicated and tentative, and would require for exposition a more advanced treatise. It must suffice to say that we are living in the dawn of a kind of atomic astronomy which looks as if it were going to do for Chemistry what Newton did for the Solar System.

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