Printed in Great Britain by The Camelot Press Limited
London and Southampton

โบคาเว ซ่บเตฎร
อโบ่คา ฎรล้จโบ

THE MECHANISM OF NATURE

CONTENTS

THE MECHANISM OF NATURE

Being a simple approach to Modern Views
on the Structure of Matter
and Radiation

By
E. N. da C. ANDRADE, D.Sc., Ph.D.
QUAIN PROFESSOR OF PHYSICS IN THE
UNIVERSITY OF LONDON

LONDON
G. BELL & SONS LTD
1930

DEDICATED
WITH FRIENDLY GREETINGS
TO
EDWARD BUXTON SHANKS
IN DISCHARGE OF AN
OLD DEBT

must not smell too much of the schoolroom, for we have neither the patience nor the compulsion which render schoolbooks read. Set to.'

This book, which I wrote as a holiday theme last July (supported, if at times the task seemed tedious, by the thought that otherwise I might have been exposed to the greater tedium of summer in Switzerland or some other playground of our public schools), is my attempt to provide a sketch of the groundwork of physical science, illustrated from recent advances, which can be read in an hour or two by a reader unversed in the study. It is intended to furnish a sufficient start to enable him to master popular expositions of individual branches of the subject, and understand the general implication of some of the new advances announced from time to time in the general Press. My purpose would perhaps have been best expressed in such a title as 'A Brief Introduction to Natural Philosophy,' which I originally intended to give to this little volume: I love the old term Natural Philosophy, and the view of physical science which it implies. The title, however, seemed too heavy for so slight a thing, and I was further assured that it would give many prospective readers a false impression, for the atmosphere of words varies from age to age, as amply attested by such words as 'Drama' or 'Statesman.'

To hang a long preface on to a short book is to say a long grace before a radish and an egg. I will spare

PREFACE

FINDING, as I do, my chiefest recreation in encounter with men who earn their livelihood by other and less desperate shifts than the service of science, I am often asked—over the coffee or suchlike modest endpiece of a spare repast—to make plain in round terms this or that achievement of our modern physics. It frequently happens, however, that the task is rendered extremely difficult by the fact that the questioner is without the first beginnings of a knowledge of the matter and the method of the science, and is, as it were, like those chemical compounds which are apt and, so to speak, anxious to absorb the vapour of water, but cannot do so easily if they are already very dry: they require a preliminary infection with moisture if they are to drink in with facility a further store.

To the demand as to in what book can be found a brief statement of the elements of the affair, such as these my questioners require, I have been forced to reply that I know of none such, and I have been urged to supply one myself. 'It must,' they say, 'be short, for we are men of the age, and cannot long give our attention to one subject: it must be plain, for we have no inclination to struggle with a new jargon, who have to do with jargon enough in our own professions: it this absurdity, and restrict myself to the hope that this trifling dish may be found sound and wholesome, and that, while it is confessedly insufficient for a full meal, it may whet the appetite for a banquet on the more substantial fare to be had in places where larger entertainment is offered.

E. N. da C. Andrade

London, March 1930.

CHAPTER I

WHAT IS PHYSICS?

La physique cherche dans son domaine à reconstruire le monde, à le déduire par voie purement syllogistique d'un principe général une fois admis.—BOUASSE.

It is the task of the philosopher to reflect upon the general nature of the happenings, material and spiritual, that make up the life of man, and to endeavour to work out some scheme which shall help to reconcile conflicting appearances and simplify, by the investigation of first principles, the complex tangle of events in which our being is involved. It is for him to try to find some kind of an answer to the eternal 'Why?' which mankind, bewildered by the problems of good and evil, of life and death, has been uttering, now in the stammer of childhood, now in the harsh voice of agony, now in the quiet tones of reflecting age, since man has been a thinking animal. The nature of appearance and reality, the meaning of truth and falsehood, the scope and implication of our knowledge, the significance of the conception of beauty—these are among the hard questions on which the philosopher must exercise his powers. They are very wide and very elusive, difficult to enunciate satisfactorily, more difficult to solve in the least particular. New points of view can be found, but how are we to judge when a real advance has been made?

The task of the man of science is more modest: it is not to answer the everlasting 'Why?' but the no less everlasting 'How?' He deals entirely with the facts of observation, and tries to reduce them into a system, so that, if we admit certain principles to start with, things which are actually known to happen systematically can be shown to follow as necessary consequences, and a method of looking for new ones is suggested. The principles themselves are chosen to suit the facts, which for the man of science are all-important—*les principes ne se démontrent pas*. Whether the principles are in the absolute sense true is not a matter on which the man of science, as such, feels called to argue: if their consequences agree with Nature they are provisionally true, at any rate. The fundamental principles of science are, therefore, often called *working hypotheses*, since they are devised with the sole purpose of furnishing a basis upon which a system may be built which appears to correspond with the behaviour of the material world, wherever we are able to make measurements for comparison. We consider that an advance has been made when a wider range of observed phenomena has been brought within the scope of one general principle.

It follows that a scientific theory may be abandoned when it has proved itself insufficient without in any way impeaching the general validity of the scientific method. Let us consider for a moment the history of the atomic theory, as an example.[1] Forty years ago it was generally held that atoms were hard, unbreakable entities, something like exceedingly minute billiard-balls, each element possessing a perfectly definite type of atom, fundamentally different from that of any other element. This hypothesis was sufficient to explain the properties of gases, for by supposing that atoms of this kind possessed certain motions obeying the laws of mechanics, results could be deduced mathematically which agreed excellently with the properties of gases as we observe them in the laboratory. By endowing the atoms with certain forces of attraction, or affinities, we could explain the general facts of chemistry. Then came the discovery of the electron, which is very much lighter than any atom, and suggested the possibility that the different types of atom might be built up of electrons. Further, the discovery of radio-activity showed that certain atoms, such as those of elements of the radium family, can fire off electrically charged particles, and so not only contain those particles as parts of their structure, but also must possess within themselves a store of energy, to provide the energy of the radiations. It was a question of either admitting this internal energy or of denying the principle of the conservation of energy, for the radio-active elements give out energy without any energy being put into them by

---

[1] The atomic theory is discussed in Chapter VII., where any unfamiliar terms receive further explanation.

us. The principle of the conservation of energy had proved too generally useful to be given up, although it was definitely suggested by some that it would have to be abandoned. The facts of radio-activity forced us, however, to abandon the idea that the atom was unbreakable, for the atoms of a radio-active element shoot off fragments of themselves and become atoms of other elements. Results of further researches could only be explained by supposing that the atom had a structure like a minute solar system, the mass of the atom being concentrated in an excessively small nucleus at the centre, and the rest of the atom consisting of electrons with wide spaces between them. This picture of the atom is discussed in the final chapter of this book, where some of the astonishing results which it explains are described, but what has just been said is sufficient to show how great a change in our ideas on this subject has taken place within a generation.

Is the critic, then, justified in reproaching the physicist in this way: *Forty years ago you told us that atoms were hard, indivisible, and unbreakable, made perfect in the beginning of things, and persisting in unworn perfection ever since. To-day you tell us that atoms are loose structures which can be very easily broken: you speak of radio-active atoms breaking up and changing to simpler atoms, and even speculate on the original formation of heavier atoms from lighter ones. What are we to believe? Your accepted theories of one generation are abandoned in the next: how can I be sure that you are right this time?* In my opinion, the correct answer is that we do not claim any absolute truth for our theories: we claim, rather, that a theory like our modern atomic theory has very great merits because all the phenomena with which we are at present acquainted are just such as we should expect if it were true. Nature, in the aspects which the physicist investigates, behaves *as if* there were atoms and *as if* they had the properties which we now claim for them. The older conception of atoms was good enough to explain the phenomena then considered, and we can still use it for certain simpler problems, where introducing the idea of atomic structure brings in needless complications; but to explain the facts of radio-activity and of spectroscopy we must introduce the newer features of the theory. The new theory is also better than the old because—as explained in Chapter VII.—it demands only two ultimate things from which atoms are supposed to be built up: protons and electrons. The fewer entities we need to assume as fundamental in order to explain things, the better our theory. We do not claim any finality for it: some new discovery may suddenly force us to modify our ideas in many particulars, but the successes of the present theory show that we shall probably have to retain many of the general features of the theory. It is an excellent working hypothesis because it has shown us law where law was not hitherto discovered, and connections between different phenomena where before we knew of no connection. It has enabled us to arrange our known facts in a more convenient and logical way, and has led to the discovery of very interesting new facts. It is justified by its works, but it is not final. Science is a living thing, and living things develop.

Some people might be inclined to go further, and claim a definite reality for atoms and electrons, and for the scheme of atomic structure which has been worked out. The great point is that, whether the man of science regards his atoms as having an ultimate reality or not, does not affect the validity of the theory: the theory is just as useful in introducing order and promoting discovery if they are merely polite fictions as if they are desperate realities, and two men who hold different views on this point will both, if they are equally adequate as mathematicians, be able to make the same predictions based on the theory, and to derive the same satisfaction from the experimental verification. To take a simple illustration: two different men may hold different views of a given politician, one holding that he is paid by a certain interest to act in a certain way, and the other believing in his integrity. If, however, he always behaves *as if* he were paid by that interest; if all his actions hitherto can be explained on that basis, and the way he will vote on any particular matter can be successfully predicted on this assumption; then he who is to represent the attitude of the man of science in our parable will say: 'It is impossible for me to find out whether he is paid or not, but because all his actions can be explained on the theory that he is, I will adopt it, since it economizes thought, in that this one working hypothesis enables me to understand all the happenings connected with the man's career. As a realist I do not greatly care whether it is true or not. I do not judge: I observe and classify my observations.' The moralist, who represents the attitude of the moral philosopher, will, however, be greatly exercised as to the existence or not of the bribes, and will be quite without any means of going behind the scenes to find out. He will merely be able to speculate. It is a more delicate problem, but one where no final solution can be reached.

On this view any particular scientific theory is a provisional tool with which we carve knowledge of the material world out of the block of Nature. It may at any moment be supplanted by a new theory, but this is only to say that when we get a better tool, which does all that this one does and something more as well, we will abandon our present tool. To refuse to use a tool because some day a better one may be invented is folly: in the same way, not to make use of a theory which has been proved to explain a great many facts, and to suggest new lines of research, because it has acknowledged flaws, and is incapable of explaining other facts, would be folly. To use another metaphor, the history of science may, as has been said, be full of beautiful theories slain by ugly little facts, but those theories did not die in vain if before their death they had subdued a vast number of jarring facts into a law-abiding populace. Nor do theories generally die a final death: often they are resurrected with some new feature which gets over the old difficulty which caused their temporary retirement.

The difference, then, between any religious belief and a scientific theory is that the former has for the believers an element of absolute truth: it is a standard by which they stand or fall, and to abandon it is dishonour and sin. The scientific theory is, however, only true as long as it is useful. The man of science regards even his best theory as a make-shift thing to help him on his way, and is always on the look-out for something better and more comprehensive.

To emphasize the pragmatic nature of scientific hypothesis the contrast between physics and philosophy has been put in the most extreme way. Some philosophers, of the school of William James, take the view that, when we say that a belief is true, all we mean is that it is useful—that all truth is justified by experience, and in no other way, just as a scientific theory is. In any case, the true philosopher cannot, of course, neglect the methods and findings of science, bearing as they do on the nature of knowledge and the character of inductive reasoning. On the other hand, the physicist is bound to feel interest in investigating the character of his assumptions from the point of view of the logician. In the old days the term philosophy was used in the most general sense, and what we now call physics was termed natural philosophy (a term still used in Scotland, and one that might well be revived) as distinct from moral philosophy. Remembering this, the purport of what has already been written is well summed up in a sentence of the great mathematical physicist Fourier: '*Les causes primordiales ne nous sont pas connues; mais elles sont assujetties à des lois simples et constantes, que l'on peut découvrir par l'observation, et dont l'étude est l'objet de laphilosophie naturelle.*'[1]

So far we have spoken of science as a whole, although we have had in mind the science of inanimate matter, in which the true characteristics of science are, perhaps, more strongly emphasized than in the biological sciences, in that more exact methods are possible. In such sciences as astronomy and physics the hypotheses are put into a form adapted for precise mathematical expression, and their consequences can be deduced with the rigorousness of mathematical reasoning. We are not content with predicting that something will happen: we require formulae which will enable us to calculate the exact magnitude of the effect to be anticipated, and our observations or experiments consist in precise measurements which we can compare, figure against figure, with the results given by the theory.

[1] The primordial causes are not known to us, but they are subjected to laws of a simple and unvarying nature, which can be discovered by observation: the study of these laws is the object of natural philosophy.

Thus in astronomy we are not content with knowing that the planets go round the sun; we must have a theory which will enable us to deduce the exact paths of the planets, and of comets, taking into account the disturbances which one planet experiences from the action of the others. The decision between Newton's and Einstein's system of mechanics can only be made by close calculation of the consequences of the two theories in certain extreme cases, where there results a slight numerical difference: we ask Nature, by meticulous measurement, which is right, and abide by her decision. The modern theories of the atom carry their conviction in virtue of the convincing closeness with which their mathematical consequences agree with, for instance, the measurements made with the spectroscope. During the Great War certain ingenious gentlemen, knowing that magnets attract iron and steel, suggested that submarines should be drawn to the shore by huge magnets. It is true that a large magnet will exert a force on a submarine, but the laws of magnetic attraction are precise, and allow us to calculate in a moment that the effect of even the largest conceivable artificial magnet will be far too small to effect this fanciful consummation. Calculation decides. The first impulse of the physicist in devising an experiment is to try to calculate the magnitude of the effect to be expected, so as to see if it is measurable, and every advance in theory reposes in a number of painstaking measurements made by previous workers. The theory of relativity itself, although a complete logical structure, arose from the fruitless search for a very slight effect which was the mathematical consequence of the current theories.

We must now try to indicate the particular scope of the science of physics, or, rather, its relation to the other exact sciences. Physics deals with the material aspect of the inanimate world, and is particularly concerned with processes in which the nature of the matter is unchanged. If the nature of the matter changes, as when copper and sulphuric acid form copper sulphate, the study belongs to the science of chemistry. Endeavouring to be more specific, we may say that the properties of matter in the sense just stated, and of energy and radiation, in all their many forms, are the particular province of physics. Text-books usually group the subject under the headings: properties of matter (which includes such subjects as gravity, elasticity, friction of all kinds, and various liquid properties, such as surface tension); heat; light; sound; electricity and magnetism. This division is a very arbitrary one, and what we are to include under each head is also very arbitrary. Physics, endeavouring to find out exact laws for the behaviour of matter and radiation, is the most fundamental of the experimental sciences,[1] as it

---

[1] By saying experimental sciences, I except astronomy, which is observational but not strictly experimental, and, of course, mathematics, which is fundamental to physics.

is the most precise and mathematical, and has its part in all the others: as they tend to become more exact they tend to come more and more within the scope of physics. The way in which physics mingles with the other sciences can be briefly illustrated by a few examples.

Mathematics is, of course, involved in every branch of physics, and, in return, physical investigation into such subjects as the conduction of heat have led to new methods in applied mathematics. Geometry, especially geometry other than that of Euclid, is deeply involved in the theory of relativity. The determination of the forces of gravity, which lies within the province of physics, is of great importance for astronomy. Astrophysics, which is the science of determining the chemical constitution and physical behaviour of the heavenly bodies, in particular the sun, is merely the application of earthly physics to heavenly ends. In such parts of chemistry as the electrical properties of solutions of different chemical substances, physics is so heavily involved that a special branch of the science, in which hundreds of workers are engaged, is called physical chemistry, while in organic chemistry the application of X-rays by the physicist has produced important results bearing on the grouping, and arrangement in space, of atoms in the molecules of organic compounds. Quite apart from this, however, it is now clearly recognized that the forces of chemical combination are electrical in nature, so that physics is now playing a leading part in general chemistry. Crystallography—and hence mineralogy—is equally indebted to the X-ray analysis of crystal structure. In geology the question of the age of the earth is one on which physics has much to say, radio-activity in particular having thrown light on this subject. In botany and in medicine physical methods are becoming more and more necessary. Even in philology, the science of speech, physics enters in connection with the study of vowel sounds, which involves the question of the resonance of the cavities of the mouth and throat, and such like studies. Meteorology, the science of the weather, depends for all her results on physics, particularly in connection with atmospheric electricity in all its aspects, including the electrical effect connected with the growth and division of raindrops. A new science of the physics of the earth (or geophysics, as some prefer to call it) treats of such subjects as earthquake propagation and the aurora borealis. The practical applications of physics in engineering and electrical engineering are so multifarious that mention is impossible, and so familiar that it is unnecessary. The method of physics is finding new scope and success every year, and the instruments invented and perfected by physics—the microscope, the telescope, the galvanometer—are constantly extending their field of usefulness.

From the point of view of physics we know something about a thing when we can measure it precisely, and find exact relations between it and other things which can be brought under the scope of our few fundamental principles. Thus we know something about the capacity for heat of different materials—that is, we can measure the amount of heat which is required to raise the temperature of a unit weight of a substance by one degree, which is called the specific heat if we take water as a standard, just as the density is called specific gravity if we take water as a standard. It is a precise quantity for each definite kind of matter: thus we say that the specific heat of aluminium at ordinary temperature is .219, for instance. We also know that the specific heat is connected fundamentally with the elasticity of the body, and with its chemical composition. But, from the point of view of physics, we know next to nothing of plasticity, the property which renders clay so valuable to the potter. The potter or the sculptor can tell by touch and experience whether a clay is in a suitable state for working, but science has not yet found a way of measuring this suitability: we do not yet know how to test a clay, and allot a definite figure of merit —a co-efficient of plasticity, let us say—so that we could say that one clay was, for instance, 1.49 times as plastic as another. Consequently, we do not know the connection between plasticity and other properties. Measurement is the beginning of physical knowledge.

From what has been said it is clear that we must have certain conceptions and laws which we take as fundamental, just as in a game there are certain fundamental rules. If someone asks why the batsman is out if he is caught, the only answer is that that is the way the game is played: the question is a meaningless one if by it the questioner means that he wants an explanation in terms of the colour of the fielder's hair, or the temperature of the air. But the question, 'What is electricity?'—so often asked—is just as meaningless, and, to do them justice, the questioners have probably never thought at all about the kind of answer they require. Electricity is one of the fundamental conceptions of physics: it is absurd to expect to be told that it is a kind of liquid, or a known kind of force, when we explain the properties of liquids in terms of electricity, and electric force is perhaps the fundamental conception of modern physics. The physicist can tell you what he means by an electric charge: he will say that when bodies are in a certain state they repel or attract one another in certain ways, and that then, as a quick way of describing that state, he speaks of the bodies as electrically charged. He can tell you the properties of these charges at rest and in motion: the connection between moving charges and magnetism: the circumstances in which there is a flow of electrical energy: how electrical energy can be converted into other forms of energy: and a thousand such things about electricity. In short, the correct question is, 'What does electricity?' not, 'What is electricity?' The former has a definite meaning, and can be answered: the latter is not a fair question in that the questioner does not really formulate his inquiry in such a way as to convey what he wants to know. If he means 'Can you express what you know about electricity in terms of something more fundamental?' the answer is definitely 'No. We must have in physics something behind which we do not go: if it were not electricity, it would have to be some other conception.'

Now that we have briefly considered the kind of knowledge which physics is, we can discuss, very briefly, some of the general results of the science.

CHAPTER II

ABOUT HEAT AND ENERGY

CONSIDERATIONS of energy enter into every branch of physics—in fact, a good case could be made out for defining physics as the study of energy and its transformation. The conception of energy in its general form was, however, of comparatively late development, for the principle of the conservation of energy was not enunciated until 1847. Let us see what it implies.

When a body moves under the influence of a force we say that work is done, and we measure the work done by multiplying the force in the direction of motion by the distance moved through: engineers, for instance, measure work done in foot-pounds.[1] If any agent possesses the power of doing work we say that it possesses energy, and we measure the change of energy by the work done.

Now, mechanical energy, possessed by a solid or a liquid or a gas, may be of two kinds, that which a body possesses in virtue of its motion, the so-called kinetic

---

[1] More correctly, foot-pounds-weight, since the force is the pull of gravity on the pound.

energy, and that which it possesses in virtue of its position, the so-called potential energy. The wind, for instance, possesses energy by virtue of the motion of the air: it can drive a windmill, which does work. The air before passing the mill-sail is moving faster than the air as it issues from the sail on the other side. It has lost speed, and the loss of energy of motion appears largely as the work which the mill is set to do. In the same way with the water turbine the stream of water loses speed in passing through the turbine wheels: in the steam turbine the steam pressure is used to create a steam wind which loses energy of motion to produce the work done by the engine. An engine could be worked by shooting bullets into a massive wooden paddle-wheel, the kinetic energy of the bullets being converted into the work done by the wheel, harnessed to a suitable mill. On the other hand, in a clock the energy which drives it is derived from position. In the old type of weight-driven clock the weights were high up when the clock was wound, and lost this energy of position as the force of gravity slowly pulled them down: the clock spring likewise possesses energy when coiled, which it loses as it moves under the influence of the stresses set up in the spring when it is wound. In a switchback railway the car when ready to start has a store of energy in virtue of its position at the top of the run.

Now it is quite clear that kinetic energy can be converted into potential energy. The switchback railway (or helter-skelter lighthouse, or any other fair-ground fantasies on the old theme) gives us a particularly good example of this conversion. As the car falls it gathers speed, the speed increasing until it reaches the lowest point of its run, when its potential energy is least: as it climbs again, and gains potential energy, it loses kinetic energy. If there were no friction it would climb again just to the height at which it started, at which point it would have lost all its speed and just cease crawling, but in practice the first hump, at the top of which it nearly stops, is always lower than the starting-point. Since at this point it has practically lost all its kinetic energy gained on the run down, and has less potential energy than that with which it started, a certain amount of energy has apparently been lost. This energy is the energy required to push the car against the friction, the rails and axles and so on, but we seem to have nothing to show for it. The clear realization of the history of this lost energy was one of the most important turning-points in nineteenth-century physics.

That kinetic energy could be turned into potential energy, and *vice versa*, was recognized in the early days of mechanics as an exact science: the great advance embodied in the enunciation of the conservation of energy was that heat is a form of energy, and that, when mechanical energy apparently disappears by friction, heat is generated. It is a familiar fact that badly lubricated bearings, when friction is high, get very hot, and that the harder it is to keep the parts moving in their bearings the hotter the bearings get; but in general the heat generated at bearings is small and escapes notice. A weight falls to the ground, gaining energy of motion, but this motion disappears when the weight reaches the floor. It actually reappears as heat, the weight and the floor being slightly warmer, but the amount of energy in question does not represent sufficient heat to be easily detectable. There are, however, cases where the amount of heat is surprisingly large. At Portsmouth Dockyard there used to be—and probably is still—a machine which stamped large rivet-holes in very thick steel plates. The amount of work done in forcing the die through the plate must naturally be very large. It used to be a favourite trick for the workman operating the machine to pick up in his horny hand the plug of metal as it fell to the floor and hand it to the curious visitor, who at once dropped it, to the delight of his friends, for the plug was exceedingly hot. The energy had been conserved—as heat.

It was the great service of Joule to prove the exact equivalence of heat and mechanical work: that whereever mechanical work apparently disappears, not only is heat generated, but an amount of heat exactly proportional to the energy that seems lost. The work can be done in various ways: by rubbing pieces of metal together, or by stirring water,[1] or—what is important for us—electrically, by pushing electric charges through a wire by electromotive force, or, in more usual words, by passing an electric current through a resistance. Heat is a form of energy. Not only is work turned into heat at all places where there is friction, including in this term such things as the 'friction' of electricity passing through a wire (a process clearly visible in the electric lamp or electric radiator), but heat can be turned into work. In every steam-engine there is an actual disappearance of heat corresponding to the work done. If all the heat generated by the furnace is measured, and allowances made for the heat given to the condenser water, not as much heat is gained by the surroundings as if the same amount of fuel were burnt without driving an engine.

There are many other forms of energy. Sound can be reckoned as mechanical energy, as explained in

---

[1] The work done in stirring water in the ordinary way—say in stirring a cup of tea—is very small, so that no appreciable amount of heat is generated: stirring the hot tea makes it cooler, because fresh layers of hot tea are brought into contact with the cold air and the cold cup. If, however, complicated paddles are used, with vanes protruding from the side of the vessel, it can be made quite difficult to move the paddle, and corresponding to the greater work done larger quantities of heat are generated, which can be accurately measured. It is interesting to note that when J. R. Mayer, who, round about 1842, was one of the earliest to realize the equivalence of heat and work, was explaining his idea, his friend Jolly objected: 'But in that case water ought to get warmer if you shake it,' which appeared to him absurd. Mayer left without saying a word, but entered his friend's room some weeks later with the words: 'So it does,' assuming that his friend, like himself, had been thinking of nothing else since. He had turned to experiment: he had asked Nature to decide.

Chapter III. Light, together with radiations of all kinds, such as X-rays or wireless waves, is also a form of energy. The energy of radiation is generally measured as heat, which is but another example of the way in which the conception of heat as a form of energy pervades all modern physics. Suppose, for instance, it is required to measure the energy of, let us suppose, a red light of a certain wave-length. The light is made to fall on a strip of blackened metal, which absorbs it practically completely, for no light is thrown back. The energy of the light is transformed into heat, and correspondingly the strip grows warmer, the slight rise in temperature being measured by delicate electrical methods. The amount of heat which would be required to produce the rise of temperature being calculated, the equivalent energy is the energy of the light. The energy of a wireless wave can be measured in a similar way by the heating effect.

Heat, then, is a form of energy. Mechanical work can always be converted into heat, and such conversion is going on all round us in Nature. At the foot of a waterfall, where the downward rush of the water is checked and dissipated in whirlpools and turbulence, the energy of motion is replaced by a slight heating of the water: the water of the storm-lashed sea is warmer than that of the tranquil ocean, other things being equal: the falling meteor becomes red hot as its motion is checked on entering the earth's atmosphere. Under certain conditions the reverse process—the change of heat into work—can take place, but only under certain conditions. That the occasions on which this conversion can take place are limited does not contradict what we have said about a given quantity of work always being equivalent to a fixed quantity of heat: the fact that we can only buy bread at certain hours and at certain shops does not affect the price of bread being fixed when we can buy it.

The relations between heat and work are the subject of the science of thermodynamics, which means literally the science of heat-power. It is the peculiarity of the thermodynamic method that it does not inquire as to the nature of heat—that is, as to whether it is a motion of molecules, or something like the trembling of a jelly, or what. In thermodynamics we are content to say that we can measure heat energy in various ways: that we have a conception of state called temperature, which we can likewise define and measure: and that we can measure mechanical work. Our object is to find relations which govern the behaviour of the measured quantities. The first great relation is that which we have already mentioned: that a certain quantity of work is equivalent to a precise quantity of heat, no matter how that work be turned into heat. This is the first law of thermodynamics, and, if we seem to be stressing it overmuch, it must be pleaded in excuse that it really is a keystone of physics. It is a denial of the possibility of constructing a perpetual motion machine, for it tells us that we can only get energy out of a machine by supplying it with at least as much energy in some form or other, either mechanical energy or electrical energy or heat. The law is, of course, nothing more than the embodiment of all our experience, but this means that every careful and authenticated observation agrees with it, and that every apparent exception proves on examination to be fallacious. The ordinary perpetual motion machines of crazy inventors are perfectly well-known types, often requiring a little ingenuity to detect the false step in reasoning. It is as profitable to organize an expedition to discover a place where weights fall upwards as to spend time planning machines of rods, levers, balls, pumps, cams, and such like to produce energy by their mere motion.[1] Nobody can say that such a place may not exist somewhere on the earth's surface, in so far as there are still unexplored territories where the downfalling habits of weights have not yet been confirmed, but, if it does, then all the most stable parts of the structure of science are naught. Most of the inventors of perpetual motion machines (who, judging from my correspondence, still exist in numbers) are the victims of self-deception, but

---

[1] Those interested in the subject will find a full history of the various types of perpetual motion machine invented up to 1860 in Henry Dircks's *Perpetuum Mobile: or Search for Self-Motive Power*, 1861–70. The work is very scarce, especially the second volume, but is accessible in many of the more important libraries.

a certain number are shrewd gentlemen who collect money to float companies for exploiting their inventions. Finding, it would seem, that most people, even prosperous business men,[1] realize to-day that you cannot get energy out of nothing, these modern inventors have turned to producing machines by which a small supply of energy is ostensibly turned into a large one. This lends itself to very plausible pseudo-scientific explanations. It is, however, equally against the first law of thermodynamics, and equally futile.

This first law does not, however, tell us anything about the conditions necessary for the conversion of heat into work to take place. It might be, for all this law tells us, possible to set up a machine by the side of a lake, to draw heat from the water of the lake and to turn that heat into work. If this could be done the lake would simply become colder than the surrounding country, and to compensate for this we should be running our machinery just as well as if we had a stream turning a water turbine. The motion of a stream, however, serves to remind us that we cannot, from a lake, get a stream of water unless we have a place at a lower level for the water to flow to: if water is to be used for turning wheels it must be higher than its surroundings. Precisely the same thing holds of a supply of heat: for

---

[1] Apparently the most credulous class of the community—at any rate, the only race which continues to produce victims for the confidence trick and the gold-brick swindle. See popular Press, *passim*.

us to be able to convert any part of it into work the supply of heat must be at a higher temperature than its surroundings. It is not only that we cannot use up the heat of ponds and lakes (I select bodies of water, because the heat capacity of water is much higher than that of stone, for instance, and because the circulation possible in water would help us to utilize the heat, if it were in any way possible to do so) and turn it into work: we could not use the heat of the furnace of a steam turbine if the whole of the engine-room were at the same temperature. We must have a condenser at a lower temperature than the furnace,[1] if we are to use up the heat of the furnace, and the bigger the difference of temperature between the boiler and the condenser, the larger the fraction of the heat which we can turn into work. This is why to-day great efforts are being made to use steam at higher and higher pressure: the higher the pressure of the steam the higher the temperature, and the greater the efficiency. Steam in itself can do nothing: on a hot planet all the water would be steam, but no steam-engine could be run, for lack of a condenser.

The second law of thermodynamics implies this property of heat, that we cannot convert it into work unless we have a difference of temperatures, and that the bigger this difference the bigger the fraction we can utilize, the fraction not utilized remaining, of course,

---

[1] In the case of a non-condensing engine, like a locomotive, the surrounding air acts as the lower temperature.

as heat, since there can be no loss of energy as a whole. The applications in engineering are obvious, but the law has such general importance that it can be widely used in physics and chemistry, and, if used with due caution, can be applied to the universe. It must, however, be used with great caution, and here we have an excellent example of the nature of a physical theory which is constructed for dealing with certain classes of problems, and often cannot be used outside those problems. The laws of thermodynamics are, in their essence, average laws—that is, we have no reason to suppose that they are true of single atoms, or of small assemblies of atoms, for we never consider anything but pieces of matter containing millions and millions of atoms when making the heat measurements on which they are based.

A refreshment caterer might work out his requirements on the basis that every thousand men eat so many sausages, so many buns, and so on, and might find that those calculations were always sufficient. They would, however, tell him nothing about what the single men eat: how many eat nothing, how many eat more than their share, how many eat only sausages. If he wanted to calculate for a crowd in a different part of the country it might suit him better to study the behaviour of the single man under different conditions, and from that construct the needs of the crowd. This corresponds to the other method of studying heat problems to which we now turn—namely the atomic method. It has the disadvantage, compared to the thermodynamic method, that it demands a more detailed knowledge to begin with: for engineering purposes, for instance, where we know that the thermodynamic method is in general sufficient, it would lead to unnecessary complications to consider the behaviour of atoms. On the other hand, it has the great advantage that, if we can get the necessary knowledge, we get an insight into the working of the machine of Nature which enables us to go behind the general effects and to examine the medley of minute complications of which these general effects are manifestations.

From the point of view of the atomic theory, we can at once say that heat energy is nothing but the energy of motion (to which must be added in some cases the potential energy) of the molecules of which matter is composed. Let us consider a gas, for instance. It consists of molecules, more complex in some gases, less complex in others, but in all cases about a hundred-millionth of an inch across, with comparatively large spaces between, moving about in all directions with an average speed measured in hundreds of yards a second. The molecules collide with one another, and lose or gain in speed at collision, so that all velocities from very small to very great are represented. Individual molecules, therefore, will have very different kinetic energies of straight-line motion, but at a definite temperature, if several million of them are considered, there will be a certain definite average kinetic energy. The molecules will also be set rotating by the collisions, and will have an energy of spin, like tops or like shells fired from a gun, which spin and move forward at the same time, except that the molecule may be spinning round an axis set in *any* direction. The molecules consist in general of atoms held together by electric forces, and the atoms may also vibrate, as if the molecule were made of balls joined together by springs, so that the molecule can possess kinetic and potential energy of vibration, like a pendulum. In short, every molecule possesses a certain amount of what we may call mechanical energy of various kinds. The hotter the gas the more lively is the motion of its molecules, or, more precisely put, the greater the average energy of the molecules. The actual process of heating can be imagined thus: the molecules of the flame or hot body, with which we put the vessel containing our gas in contact, are in more energetic motion than those of the cold vessel, and by beating against them communicate some of their energy to them. The molecules of the vessel in turn strike vigorously the gas molecules as they come in contact with them, until they too gain in energy. If the vessel be closed the more lively beating of the gas molecules against its sides produces the rise in pressure which we know takes place when a gas is heated in a sealed space.

In a liquid we likewise have energy of motion of the molecule, but it is not so simple to analyse, since, whereas in a gas the molecules have comparatively long, straight paths between the collisions, in a liquid they are so crowded together that the motion is controlled by the forces of the neighbouring molecules. In a solid the molecules are anchored to definite spots by the forces of cohesion, and vibrate about that spot like balls held by springs. In all cases, however, the heat energy is simply the energy involved in the motion of the molecules.

This motion of the molecules is a random motion. If we could fix our eyes on a given molecule, and follow its career, we should see it moving now in one direction, now in a totally unrelated direction, and if we could throw a glimpse at all the molecules at once, we should see that different molecules were moving in different directions. Instead of behaving like well-drilled soldiers, they resemble an aimless crowd. Contrast this with what we do when we push a piece of matter in a given direction, say, for instance, when we slide a block of wood along a table. Every molecule in the block has now, as well as its irregular motion, a perfectly definite motion which it shares with every other molecule of the block: the actual motion of a given molecule will, of course, be obtained by considering the joint effect of the common motion and of the irregular motion. We have, by moving the block as a whole, introduced an element of order into the motion. If we just give the block a push it soon comes to rest owing to friction, and we know that heat will be generated where it rubs along the table. This generation of heat means, as we have seen, a general increase in the irregular motion of the molecules in the neighbourhood of the surfaces where friction takes place. In other words, instead of saying that our mechanical energy has been converted into heat, we can say that the energy of the regular motion which we imposed on the molecules when we pushed the block has been converted into energy of irregular motion of the molecules. This represents a general tendency in Nature. Regularity of motion tends to disappear, and to be replaced by irregular molecular motion. Everything tends to 'mixed-uppedness.'

Let us consider a few examples. Suppose we have two bodies, at different temperatures, in a room—say a furnace and a tank of water. There is a class-distinction created by man: the molecules of gas in the furnace have on the average a greater energy than the molecules of water in the tank. If everything is left to itself the whole room will eventually come to one temperature: the fire in the furnace will have gone out and the furnace will have shared its heat with everything else in the room. A million molecules taken at one place will have exactly the same average energy as a million molecules at any other place. By a machine we could have converted a certain amount of the heat of the furnace into work: we could, say, have run a dynamo and charged accumulator cells which would then run one of the old-type electric cars for us. This is a regular co-ordinated motion, all molecules of the car having a common drift imposed on them. But what will have happened when we have run our car out and back home again? The accumulator will have run down, and we shall have nothing to show for our energy, being exactly where we started. Where has it gone? In friction of wheels on the road, of axles in their bearings, of chassis against the wind. All our regularity has vanished, to be replaced by the additional irregular motion consequent on the slight heating of road, bearings, and wind and chassis—very slight heating, except, perhaps, in the case of the bearings. Nature has won. We may say, then, that man represents a ceaseless struggle to impose an element of regularity useful to himself on the irregular molecular motion of the bodies that compose our world.

If we consider bodies of visible size, containing millions of millions of millions of molecules, we are led to exactly the same result whether we apply the gross laws of thermodynamics or the individual method of molecular physics. But suppose we consider molecules themselves, or very small particles. The molecules in a given piece of stuff are in perpetual motion: if the piece is at a high temperature the average motion is more vigorous than if it is at a low temperature. We know, however, that in the one piece of stuff some of the molecules will have a high degree of motion, the others very little: the temperature which we measure with a thermometer indicates an average only. Suppose we could pick out all the little, inconceivably little, bits where the molecules were in vigorous motion, and put them in one place, and all the little bits where the molecules were comparatively quiet, and put them in another place, we should have obtained from a body at one temperature, according to our thermometer, two pieces which thermometers would show to be at different temperatures. To imagine how this might be done, suppose, as Clerk Maxwell did, that we have a vessel of air, with a partition across, pierced by a minute hole closed by a sliding door, worked by a very intelligent microbe. When he sees a fast molecule coming from right to left he opens his door and lets it through: when he sees a slow molecule coming from left to right he lets that through. Soon he will have all his energetic molecules on the left, all the sluggish ones on the right. There will be, of course, a redistribution of energy among the molecules in each compartment, but, on the whole, the energy in the compartment to which only fast molecules were admitted will be greater than that in the other. The temperature will be correspondingly higher in the one compartment than in the other. The microbe need have done no work, for his door can be imagined as light and as well lubricated as we like. Therefore, from a body at one temperature we have, without doing work, obtained bodies at two different temperatures, with which we can work a little engine. It is, however, against the second law of thermodynamics for us to be able to obtain work from a body originally all at one temperature. What is the explanation?

The explanation is simply that the laws of thermodynamics only apply to visible pieces of matter, and that they suppose that we cannot employ microbes and play with molecules. If we could drill molecules, if we could, without doing work, interfere with the 'mixed-uppedness' of Nature, we could violate the law. If the caterer, whom we cited before, could go and talk to each individual man in his crowd of a thousand, no doubt he could influence the demand for particular viands in any way he liked. As it is, he must arrange his supplies to suit what he knows to be the bulk demand of a large crowd. Our ordinary laws of physics, engineering, and chemistry are laws for the behaviour of crowds of molecules.

When we come to think of things in terms of molecules we have to introduce probability instead of certainty. Suppose I hang up a coin in the air. The millions of millions of millions of molecules around it are moving at random—some fast, some slow, some up, some down; on the whole, the blows in different directions average out, and the coin stays put. Suppose, however, that it so chanced that at one particular moment there happened to be a large excess in strength or number of molecular blows on one side, say underneath the coin, what then? The coin would jump. Is it impossible that there should be an appreciably larger pressure produced by molecular bombardment in one particular direction than in other directions? Is it impossible that a penny fairly tossed shall come down heads six thousand times or more in ten thousand tosses? The answer in both cases is, 'No, not impossible, but exceedingly improbable.' Actually, in the case of the penny, it requires a number with eighty-seven zeros to express how improbable it is: a million million to one chance is exceedingly likely compared to it. Practically, we may just as well say that it *is* impossible, but philosophically there is a difference. Thermodynamics says bluntly: 'Impossible' in such cases.

Our citation of coin-tossing suggests a further step. Suppose we toss only a hundred times: is it so wildly improbable that there will be sixty heads or more? No, it is only thirty-three to one against. And suppose we toss only ten times: the chance of six heads, or more, is quite large, only about 2 to 1 against. In the same way, suppose we take a very minute particle, of, say, about a thousand times the diameter of a single molecule, suspended in a liquid or a gas, we can calculate what is the chance that the force of the molecular blows which it receives on one side may exceed the force of the blows which it receives on the other side sufficiently to produce a perceptible movement. The result is that with a particle of this size, which can be seen with a high-power microscope, we should expect a small irregular movement, big enough to be perceived by the microscope, due to the agitation of the molecules with which it is surrounded. The smaller the grain the livelier the agitation to be anticipated. On the other hand, the chance of visible movement of any grain that can be seen by the naked eye, in a liquid protected from currents, is so exceedingly small that it is hopeless to try to observe it.

It appears, then, that if our conception of heat as molecular energy were true we should be able to see, as it were, a slow-motion picture of this agitation in the irregular movement of microscopic grains suspended in a liquid. As a matter of fact, such a movement was discovered long before its theoretical meaning was realized. About a hundred years ago the English botanist Brown observed that minute particles in certain plant fluids were perpetually quivering, moving hither and thither in directions quite independent of one another, unlike the motes in a sunbeam, which go in drifts, and indicate general currents in the air. Gradually, by repeated experiment, towards the close of the nineteenth century the various superficial explanations of the movement—that it was due to the shaking of the building, to currents caused by the illuminating light, and so on—were conclusively disproved. Finally, Professor Perrin undertook systematic measurements, regarding the grains as enormous molecules jostled by the ordinary molecules of the liquid—Gullivers which had invaded the liquid Lilliput and were suffering the will of the multitude. From these measurements, performed on a very small drop of water discoloured with the paint gamboge, which breaks up into minute spheres of horny substance when rubbed in the liquid, he was able to calculate not only that the movement of the particles was perfectly explained by the heat movement, but also to deduce the number of molecules in a given weight of any substance. The number of molecules in an ounce of water is something under a million million million million, which means that if every man, woman, and child in the world were turned to counting them, and counted fast, say five a second day and night, it would take about four million years to complete the job. This figure has been confirmed by a variety of experiments based on quite different principles.

In a liquid, therefore, microscopic particles may be thrown upwards by the molecular agitation. If a microbe were building a house he could wait to have his bricks thrown up to him: the energy required would be taken from the molecular energy of the liquid, which is heat, so that by the time the microbe's house were built the liquid would be a little cooler, to compensate for the energy required to raise the bricks. The microbe would have apparently violated the second law of thermodynamics, but this does not distress us, as the second law only governs the behaviour of matter in bulk, and does not apply if we can employ creatures small enough to make a discriminating interference with the molecular mechanism. The bigger the particles the less probable a perceptible movement due to molecular agitation: with a visible brick we might have to watch for millions of centuries to see it jump, but we cannot say that the jump is absolutely impossible.

This statistical way of regarding physical problems, this conception that what we see is just an average effect, and that we must be very careful before we attribute to individual molecules properties and laws which we have discovered from observing matter in bulk, is assuming a very large part in modern physics. The conservation of energy itself is a law which entirely suits all our ordinary observation, but recently it has even been suggested that it may not apply to processes happening within the atom. The point is a moot one, but it illustrates the caution, the scepticism—one might almost say the timidity—which has found a place in scientific thought as a result of the many baffling phenomena which have come to our knowledge in the last ten years. At one time universal validity was attributed to any law which had a success with a wide range of experiments: to-day the utmost care is taken in distinguishing between facts of observation and speculative processes introduced to explain them, and, as far as possible, the theories deal only with the facts. At the beginning of the century there was even a movement against the atomic theory, as at that time there was no convincing *direct* evidence for the existence of atoms and atomic agitation; but the experiments on the Brownian motion, and, since then, a range of other fundamental experiments, have now established the objective existence of atoms as far as the objective existence of anything can be established.

What we have said so far about heat and atomic motion applies very well under ordinary conditions, by which we mean in particular at ordinary temperatures. At extremely high temperatures or extremely low temperatures, however, we are met by very interesting new phenomena. During the last thirty years a technique of reaching exceedingly low temperatures has been worked out, mainly by Professor Kamerlingh Onnes, at Leyden in Holland, which has enabled us to get within less than one degree of the absolute zero of temperature. This absolute zero is a very important conception: it represents a temperature below which we cannot conceivably go. To discuss it in any way fully would mean an examination of the question of how we define a scale of temperature, which is by no means as simple as it may seem, especially at low temperatures. It is, for example, no help to say that equal expansions of the mercury in the thermometer represent equal rises of temperature, because if we took another substance in our thermometer we should get a slightly different scale, and there seems no point in giving mercury the preference. Anyhow, mercury freezes at 40 degrees Centigrade below zero, and so cannot be used to give a scale at such low temperatures. Theoretical reasons indicate that an ideal gas, without the slight traces of memory of a liquid state which actual gases show in their behaviour, would be the right substance to use to measure temperature. There is no such thing, of course, as an ideal gas, but we can calculate how far its behaviour deviates from that of any real gas, just as we can measure how far any real solid deviates from perfect rigidity. It so happens that the temperature scale of a perfect gas agrees pretty well with the mercury thermometer, with equal divisions, over the range of temperature for which mercury can be used. Now, this ideal gas at a certain degree of cold would shrivel up to no volume at all, and that degree of cold represents the absolute zero, below which we cannot go by any conceivable process. We cannot think of any substance as having less than no volume. The absolute zero so indicated is 273 degrees Centigrade below the temperature of melting ice; the boiling-point of water is, of course, 100 degrees Centigrade above the temperature of melting ice.

At the exceedingly low temperatures reached in the laboratory of Kamerlingh Onnes every known gas becomes first liquid and then solid: the last gas to stand out was helium, and that was solidified in 1927 at a temperature only about one degree above the absolute zero. We can find out something about the energy of the molecules of a substance by measuring the specific heat, which is the heat which must be added to raise the temperature of the substance by one degree. An astonishing result is that at these low temperatures the specific heat is nearly nothing; for instance, it requires only a twenty-fifth as much heat to raise the temperature of a pound of aluminium from 30 degrees above absolute zero to 31 degrees above absolute zero as it does to raise it by one degree at ordinary temperatures. These very low specific heats at low temperatures have very great importance for the quantum theory, and we mention this in Chapter VI.

At these exceedingly low temperatures many metals lose practically all resistance to the flow of electricity or, as we say, they become super-conductors of electricity. The term 'super'—often used by cinema magnates without any very striking justification—really is justified in this case, as may be judged by the fact that a thousand miles of lead wire at five degrees above absolute zero offers no more resistance to the passage of electricity than one inch of copper wire of the same diameter at ordinary temperatures. Investigation of this effect is one of the most fascinating fields of physical research, for a satisfactory theory is yet to seek. All the properties of matter at these exceedingly low temperatures are, in fact, remarkable and full of interest.

At the other end of the scale we might suppose that as the temperature is raised higher and higher the molecules simply rush about more and more vigorously, and the older point of view was that this was the case: the properties of gases at higher temperatures were taken to be just a natural extension of those at the lower temperatures. We know now, however, that it is incorrect to treat the molecules as little balls whose speed of motion can be indefinitely increased by raising the temperature. When the temperature rises above a certain point the molecules begin to fall to pieces, to dissociate into the atoms which compose them, just as a cluster of balls glued together would break up into the individual balls if it were vigorously struck. If the temperature is raised still more the atoms themselves begin to come to pieces, losing their electrons group by group, until nothing is left but atomic nuclei and unconnected electrons.[1] Temperatures which remove a few of the electrons from atoms can be attained on earth, but the temperatures at which all the electrons are stripped from the nucleus as the seed is knocked from a dandelion head, leaving nothing but the central knob, can only be attained in hot stars. This conception of atoms

---

[1] The modern theory of the structure of the atom is discussed in Chapter VII.

which are broken up when the impacts of atom on atom are sufficiently vigorous has proved of the greatest importance in astronomy, for in the interior of stars the prevailing temperature seems to be in the neighbourhood of 40 million degrees Centigrade, as against the highest terrestrial temperature of a few thousand degrees. Once more the application of laws obtained for one set of circumstances to quite different circumstances would arouse grave difficulties. We are led, whether we want to or no, into the realms of atomic structure. The older laws of heat, which took no account of anything but the behaviour of matter in bulk under what we may call engineering conditions, do not suffice to explain either the problems of heat radiation at very high temperatures or of heat vibration at very low temperatures. We must postpone what we have to say on these subjects until we have had a word about the modern ideas.

CHAPTER III

ABOUT SOUND AND VIBRATIONS

THERE is no branch of physics in which we are not brought sooner or later—generally sooner—to the study of vibrations, the study of waves, the study of processes which repeat themselves over and over again as does, to take the simplest case, the motion of a pendulum. The physicist calls such processes periodic phenomena. All of them have certain fundamental characteristics, of which the most obvious is the time period—that is, the length of time in which one cycle takes place. A pendulum takes so long to execute one complete beat, there and back, and then starts over again: a spinning flywheel takes so long to carry out exactly one revolution, and then every part of it is in exactly the same position as before and the next revolution begins: a violin string sounding a given note requires just such a fraction of a second to complete a full swing backwards and forwards: a wireless wave, which is an oscillation of electric and magnetic force, repeats itself at a given place with just such an interval between the exact repetitions. All vibrations, oscillations, and waves, then, possess a characteristic periodic time. Another way of stating the same thing is that they possess a characteristic frequency, the frequency being the number of complete vibrations in unit time —say one second. Of course, if we know the periodic time, then we can find the frequency, and *vice versa*— if the periodic time is $\frac{1}{10}$ of a second, the frequency is 10 vibrations a second. Which we use is a matter of choice. In the case of very rapid alternations, like those of a sound vibration, and still more so those of a wireless wave, it is more usual to state the frequency, since it is more convenient to speak of, say, a frequency of 256 vibrations a second than of a periodic time of $\frac{1}{256}$ of a second.

The study of sound is really the study of vibrations of material bodies. Light vibrations come to us from the sun across space empty of matter, so that, whatever light may be, it is not a swinging of material substance, in the ordinary sense. Sound, however, requires a solid, or a liquid, or a gas if it is to travel: the man in the moon could see any light signal we might make, but could not hear any shout, however loud. Solids convey sound very well, a fact familiar to the heroes of old adventure stories, who put their ears to the ground to hear the hoof-beats of approaching horsemen. A very effective experiment on the propagation of sound through a wooden rod some thirty feet long was shown by Tyndall at the Royal Institution. In the basement below the lecture-room, separated from it by two floors, was a man playing a piano. A wooden rod resting on the sound board of the piano passed through holes in the floors into the lecture-room. When a wooden tray was placed on the top of the rod the playing of the piano became distinctly audible in the room. The sound vibrations, passing along the rod, threw the tray into vibration, and the vibrations of the tray communicated themselves to the air. The experiment could be made more startling by placing a violin or a harp at the upper end of the rod, to act as the sounding board. Turning to liquids, bathers can easily verify that water conveys sound very well, for the beat of a ship's screw can be detected when the ship is still far off by putting the head under water. Elaborate methods were worked out during the war for detecting the positions of submarines by the sound of the engine conveyed through the water to special microphones. As for gases, sound ordinarily reaches our ears through the air, and there are many simple experiments showing that it passes equally well through other gases. The old experiment of an electric bell, driven electrically or by clockwork, and carefully suspended by thin rubber threads in a jar from which air is then pumped out, shows, on the other hand, that sound cannot pass through a vacuum, for as the pumping proceeds the ringing becomes fainter and fainter, until finally nothing can be heard. Of course, if the bell is placed on the plate at the bottom of the jar, instead of being hung by thin threads which conduct the sound badly, the sound passes through the stand to the table, and communicates itself to the air in the room.

The study of sound includes three separate divisions: the behaviour of the sounding body, which is a study of vibrations; the passage of the sound from the source to the place where it is detected, which is a study of waves; and the way in which the ear acts, which is included in the general question of the behaviour of sense organs. The perception of sound by the ear involves, of course, physical considerations, but it is generally considered a matter of physiology, and will accordingly be put on one side here. As regards the origin of sound, we are lucky in being able to observe directly the way in which the vibrations take place, which we cannot do in the case of light. It is true that the frequency of the vibration of a body giving out a musical note is so high—e.g. 256 per second in the case of the middle C—that the movement cannot be followed by the unaided eye. A violin-string or a tuning-fork when sounding appears merely blurred, but there are plenty of ways in which the mode of vibration can be analysed.

The pitch of the note is fixed by the number of vibrations a second and nothing else: thus, whether the middle C is sounded on an organ-pipe or a violin or a piano, there are 256 complete cycles of vibration of the air column enclosed in the pipe, or of the string of the violin or piano respectively, in a second. In this way it is possible to give the number of wing-beats a second of a bee, or wasp, or a gnat, simply by tuning a string to the note of the humming of the insect, and afterwards finding out the number of vibrations per second in the note of the string, either by calculation from the dimension of the string and the tightness with which it is stretched, or by some other method. Of course, if the listener have an accurate enough ear to name precisely the position of the note of the insect in the musical scale, the problem is solved at once, since the frequency of each note is known: thus if a bee is humming the G below the middle C its wings must be beating 192 times a second, while a common fly sounding the F above the middle C must be making about 340 wing-movements a second.

The loudness of the note is given by the vigour of the vibration, the greater the departure of the string, or other sounding body, from its position of rest the more intense being the sound. The character of the note, the timbre or tone-colour, as the Germans call it, is given by the character of the vibration. The character in question is the peculiarity by which, for instance, the note of a trumpet differs from the note of a piano, although both may be sounding the middle C, with equal loudness. If the sounding body move out at a uniform speed to its extreme position, and then returns at uniform speed, passing to the other extreme position, we have a different character of note from what is the frequency of the fundamental note, the time period of the fundamental just includes a whole number of vibrations of the overtones: a complete cycle is still included within the time period of the note itself, and the only effect of the overtones is to alter the form of the vibration—to modify, for example, the instant within the time period when the vibration is half-way to its greatest value. The ear possesses the remarkable power of analysing the complicated wave form into its simplest parts, and picking out the various harmonics which are sounding simultaneously. It is worth noting, perhaps, that the eye has not this power of analysis: a white light, for instance, can be produced by mixing all colours in suitable proportions, by mixing only two colours in suitable proportions, or by mixing three or more colours. The final white can be made to appear the same to the eye no matter how it is produced, and in a similar way the eye cannot, without instrumental aid, detect what pure colours have been combined to produce any particular mixed colour, or chord of colour, as we may call it to strengthen our analogy.

What is produced by a plucked string is, then, a wave of characteristic shape. In the same way many instruments sounding simultaneously produce a wave of still more complicated shape, but, naturally, however many different sounds are going on at once the result at a given place in the air can only be one movement. Any given little bit of air cannot be in more than one place at once: what that place is at a given instant is determined by the combined effect of all the sounds passing the given spot. To take an illustration, no matter how complicated the transactions in a shop, how many purchases and sales, if the total balance be struck at any moment there can only be one definite sum as a result, although it needs a careful analysis to see how that is reached. The result of the orchestral air-pushing is, then, that a wave of very complicated shape is launched on the air, the air particles striking a balance of the various pushes and pulls which they experience at any moment. This complicated wave is then analysed by the ear, the more trained the listener (other things being equal) the more complete being the analysis. When a record is made the diaphragm, which governs the needle which cuts the indentations, is moved by the complicated wave so as to record the resultant motion produced by all the instruments. Similarly, when the record is played the indentations move the diaphragm of the sound-box in the same complicated way, with little jerks, ripples, and peaks of motion imposed on the fundamental wave, and a wave is launched of exactly the same form as that produced originally by the orchestra. Naturally, therefore, the result on the ear is the same.

It is well, perhaps, to devote some little consideration to the nature of a wave. The breaking wave on the beach which is conjured up by the phrase, is, unfortunately, an exceedingly bad example of what we mean by a wave in physics: the ripple on a pond produced by dropping in a stone, or the long, smooth rollers out at sea are exceedingly good examples. The characteristic is that, at any given spot, a periodic, or pendulum-like, motion is taking place, and no forward motion of the medium—air, water, or what not—through which the wave is moving forward. Little boys who, when their boats are becalmed on the pond, throw stones or bricks beyond them so that the waves produced shall bear the boat back, have experience of this (which, however, does not seem to profit them). As the wave reaches the toy boat the main effect is to raise it up and down: it does not move it forward perceptibly. A cork on the pond bobs up and down as the ripple passes it, but does not move along with the ripple crest. What is propagated is the form of the wave.

A good illustration of what we mean by a wave can be seen when a long line of soldiers dresses by the right. If the man on the extreme right were to make a small movement forward every man, dressing by his neighbour, would successively make a small movement forward, and a ripple would run along the line from right to left, but no individual man would be moving from right to left. If the right-hand man were to make a small movement forward and backward at quite regular intervals, say every two seconds, we should have a perfect example of a wave of frequency thirty a minute. Every man in his place would likewise be making a movement forward and backward thirty times a minute, but each man would be a little behind his right-hand man in this movement. If the men were halted sharply the line would be wavy, the successive distance between men who were in the same position and at the same step of their movement being called the wave-length. When the wavy movement was in progress, at one moment one man would be at the extreme forward position, at the next moment it would be his left-hand man. The position of the particular man in the forward position would run along the line, corresponding to the advance of the crest of a wave.

In the case of the line of men, the movement of any individual man is at right-angles to the direction in which the wave is travelling, namely at right-angles to the line. Such a wave is called a transverse wave. A wireless wave or a light wave is this kind of wave: there is an electric force and an accompanying magnetic force, at right-angles to the direction in which the wave is travelling, and the strength of these forces is fluctuating periodically all the time the wave is passing. If we could hang up an inconceivably small electric charge and watch it, and a wireless wave[1] were passing through our house from the north, then the electric charge would bob up and down vertically under the influence of the periodic electric force, like the cork on the water

---

[1] Actually what we say assumes the wave to be polarized, but this is a simplification that does not affect the general picture.

ripple. At the same time an inconceivably minute magnetic pole would move backwards and forwards horizontally from east to west and back again. A sound wave in air, however, is not a transverse wave. Imagine again our line of men, but this time in Indian file, and let each one place his hands on the shoulders of the man in front of him. If now someone gives the rear man a violent push he will move forward in the direction of the line, and push the man in front of him. A jostle, as it were—that is, a place where the men are nearer to one another than they ought to be—will run along the line. If, now, a strong man takes the rear man and pulls him back he will pull the man in front of him, and so on, and a pull will run along the line. If the rear man is rocked backwards and forwards, jostles succeeded by pulls will be continually propagated along the line. Such is a sound wave in air, regions of pressure and rarification moving forward with what we call the velocity of sound. The actual movement of a particle of air is backwards and forwards *along* the line on which the wave is travelling: we speak of a longitudinal wave.

We can have only longitudinal waves in a liquid or a gas, for there is no force to pull a particle back and make it swing if we pluck it aside, as there is if we pluck a string aside. We can, however, get transverse waves in a string, as can be seen by shaking one end of a long cord, and we can have still other forms of waves in a long bar, such as waves of twist. The form of the sound wave in air is given by the sheet of instructions, as it were, which govern the movement backwards and forwards of the individual particle. If it swings gracefully to and fro like a pendulum we have the simplest possible wave, but it may move jerkily with little sweeps of advance, or even with little advances and retreats on top of the main movement, as if each man in our Indian file had a fit of shivers as well as a gentle sway backwards and forwards.

If in a wave there is no general movement forward of any particle from the spot about which it swings, nevertheless the *state of motion* does move forward in the direction of the wave. As long as the rearmost particle is shaken every other particle vibrates: if the rearmost particle is stopped, then, as soon as the wave from its last movement has passed a given spot, that particle at that spot is still. This means that energy is carried forward along the wave, which is, in any case, pretty clear. If, by dabbling my hand up and down in the water I can make a cork twenty yards off move up and down, then clearly I am supplying it with energy which travels out with the ripple; the water under my hand does not travel out, but the state of motion does. In all waves, then, there is an actual stream of energy in the direction in which the wave is travelling.

The changes in pressure and the movement backwards and forwards of the air in a sound wave are ordinarily very small. A sound is distinctly audible even when the greatest changes of pressure in the wave are only a few hundred-millionths of the atmospheric pressure, and the greatest swing of the particles is a few hundred-millionths of an inch. Correspondingly the energy of an ordinary sound wave is minute. But if a sound wave be sent through a material which opposes a strong elastic resistance to compression, like an ordinary liquid, and nevertheless, by strong pressure, the oscillatory movement be made considerable, a very great amount of energy can be put into the wave, and travels along with it with very little loss. Following these principles, an actual system of transmitting energy by sending what are virtually sound waves along liquids enclosed in pipes has been devised by M. Constantinescu. At the sending end, a little piston which, in the case of a particular 10 horse-power generator, is about an inch and a half in diameter, with a one-inch stroke, is given a rapid to-and-fro motion by the engine whose power is to be transmitted. In the case cited the greatest pressure reached during the stroke is 1,500 pounds per square inch. The energy in a sound wave increases very rapidly if the frequency is increased, other things being equal, because the speed with which the particles of matter are swinging is proportional to the frequency, and the energy depends upon the square of the speed. The frequency of the stroke is therefore made as high as conveniently possible—40 strokes per second with the 10 horse-power set in question, which gives a note E two octaves below the middle C. The waves generated by the high-speed piston travel along a pipe line, 240 feet long in our example, and at the other end drive an engine of any desired kind, by pushing and pulling a plunger similar to that which starts the wave, with an energy equal to that put into the waves at the generating end, except for small frictional losses. It must be clearly understood that when the piston moves in at the starting end the whole body of the liquid does not move and push the piston at the far end: rather, the inertia of the liquid leads to a region of high compression at the piston, which runs through the liquid in the pipe and pushes the piston at the far end, and, similarly, when the generating piston is withdrawn, a region of low pressure (or stretch of the liquid, or tension, whichever term we choose to employ) is created which runs through the liquid and pulls the far piston when it reaches it. There is a true wave motion, with a musical note, running through the liquid, and delivering energy, just as much as if a train of men were to set out, alternate men carrying vessels of high pressure air, and vessels in which a vacuum had been produced, each man with a pressure vessel being supposed to connect it to an engine at the end of his journey, and so push out the piston, while in between, the vacuum men connect their vessels and send it back. The Constantinescu method has been applied in mining operations.

It may be noted that it first came into prominence during the war, when the inventor utilized it to synchronize machine-gun fire with the revolutions of an aeroplane engine, so that the aviator could fire through his propeller without hitting the blades. By connecting to the gun a tube of liquid carrying waves generated by the engine the firing could be so timed that the bullet always passed at the right moment.

Transmission by wave motion is commoner than one is apt to think. For instance, if a long steel rod is put against a rivet and struck sharply with a hammer at the far end, a wave of compression runs along it which delivers the blow to the rivet. This principle has been used to measure the energy of detonation of an explosion, using a small charge of explosive to deliver the blow, and making the wave throw off a small piece of metal at the far end, the speed of which can be measured in a simple way. Even with a hammer and a steel chisel the blow is not transmitted instantaneously from the hammer to the object under the chisel edge: the wave of compression takes about a twenty-thousandth of a second to pass from one end of the chisel to the other.

A sound wave, in addition to the rapidly alternating push and pull which it creates, exerts a general forward pressure whenever it meets a surface: if it is absorbed by the surface the pressure is only half as great as if it is reflected, completely turned back on itself, by the surface. As a matter of fact, this pressure is a property not only of sound waves, but of all kinds of waves, although wherever the energy of the wave, of whatsoever nature it be, is small the pressure is also very small. It was at one time believed that the little radiometers often seen in jewellers' and opticians' windows, little systems of delicately pivoted vanes enclosed in an exhausted bulb, which rotate rapidly when sunlight falls on them, showed the pressure of light, but actually in this case the effect is a heat effect associated with the traces of gas left in the bulb. The pressure of light can, however, be shown experimentally by using very delicate suspension of the vanes instead of the comparatively coarse pivot, and securing very high exhaustion of the bulb, but it demands great skill to measure this pressure accurately. The pressure of sound can also be shown with a delicately suspended disc, but the sound has to be very loud to produce measurable effects.

We have frequently cited light in speaking of sound, since they both have certain common properties due to the fact that they are both wave motions, although sound waves in air are longitudinal, while light waves are transverse. Similarly, sources of sound, which are mechanical vibrating systems, have close analogies in other branches of physics, especially in the oscillating electrical systems with which wireless telephony and broadcasting have made most of us familiar. In systems of condensers, capacities, resistances, and triode valves charges of electricity oscillate with certain frequencies, certain amplitudes, and a certain wave form, and give rise to electro-magnetic waves which travel out through space, just as in a gramophone sound-box a system of masses, springs, and yielding substances, such as rubber rings, oscillate and start sound waves on their journey through the air. The connection between the electrical and the mechanical sources of sound, the wireless oscillator and the gramophone sound-box, is much closer than might be expected: inductance, capacity, current, and charge in the one case, for instance, correspond exactly to mass, yieldingness[1] of spring, speed of moving part, and distance through which moving part has moved in the other case. Similar formulae can, with such like correspondences, be applied to either case. This is not only a very good example of the kind of generality which we often meet in mathematical physics, but it is also a case that has had considerable practical importance. The great improvement that has taken place in the gramophone since 1925 has been due not only to the application of wireless apparatus in the recording of music, but also to the application of the knowledge, acquired in the last few years, of the behaviour of oscillatory electricity in complicated circuits to the problem of oscillating mica or metal diaphragms exposed to all the modifying influences which exist in

---

[1] Called 'compliance' by the workers in this field. It is the reciprocal of stiffness.

the gramophone. The re-designing of sound-box and horn was carried out with the aid of mathematical analogies drawn from electrical cases, which have been so thoroughly studied of late. A race of men is, in fact, arising who think of the electrical quantities as fundamental and familiar, and explain the mechanical quantities, which seem more familiar to most of us, in terms of them. In earlier days it was customary to build mechanical models with masses and cog-wheels to explain electrical self-induction: to these men, however, self-induction is a fundamental thing that needs no explanation, and they would make use of what they know of it to help them to understand the behaviour of the simple mechanical model.

There are other direct relations between sound and wireless technique which are now marching hand in hand. By ordinary means, such as tuning-forks, or whistles, or strings, it is very difficult to obtain a very high note in any intensity. By electrical methods it is, however, possible to bring comparatively thick slabs of a rigid material, actually quartz crystal, into vibration, when, on account of the large forces which tend to pull the slab back into its old position the moment it is deformed in any way, the note is extraordinarily high. Professor R. W. Wood has, in this way, produced frequencies of 300,000 vibrations per second, and occasionally even higher frequencies have been obtained. Such a 'note' is not, of course, audible, the limit at which most people can hear anything at all being about 17,000 per second—about six octaves above the middle C. Sound waves of these extreme frequencies, of hundreds of thousands of vibrations a second, produce extraordinary effects. The actual to and fro movement of the particles of the liquid or solid through which the waves are travelling is a few hundred-thousandths of an inch, yet, on account of the rapidity with which the motion takes place, the energy of the wave is very great, and certain properties of wave motion are exhibited in an exaggerated way. The pressure of sound, for instance, which, as has been stated, requires a very delicate instrument to detect it in the case of ordinary sounds, even when they are unbearably loud, shows itself in many striking ways with these ultra-sonic waves, as they are called. If the oscillating quartz plate which generates the waves be put flat on the bottom of a vessel of oil, so that the waves travel upward through the liquid, the surface of the oil is raised in a mound three inches high by the sound pressure, and a fountain of oil-drops surmounts the mound. The pressure will support a plate loaded so as to weigh six ounces. The energy of the waves shows itself in other remarkable ways. If one end of a fine glass rod be dipped in the oil, and the other end held between the fingers, a groove will be burnt in the skin, due to the friction between the surface of the skin and the rapidly oscillating surface of the glass. Similarly, if a tapering rod be placed with the thick end in the oil, the upper point can be made to burn a hole in a piece of wood. The biological effects of the waves, whose length is measured in hundredths of an inch (instead of in feet, as with ordinary sounds), are also astonishing. Small fish and frogs are killed if the sound-waves are sent through the liquid in which they are swimming. The contents of living cells are stirred up and small and fragile living bodies torn to pieces. Blood corpuscles are ruptured when the fluid in which they swim carries the waves.

We see, then, that both from the engineering and from the laboratory side methods have been found for throwing large energies into sound waves: in the one case at frequencies which are comparatively low as sound waves (but very high from the engineering point of view); and in the other case at frequencies which are very high as sound waves, but very low compared to light vibrations, say. The properties of vibrations are strikingly exemplified in the results. We are still, perhaps, far from the day when we can fetch down city walls with the sound of trumpets, as was done at Jericho, but a beginning has been made.

CHAPTER IV

ABOUT LIGHT AND RADIATION

If a narrow beam of white light—say sunlight, but the light from an electric lamp will do just as well—from a slit pass through a prism it becomes a bundle of narrow beams fanning out so as to give a long band where it falls on the screen, in place of the line of light which it forms if no prism be interposed. The band is coloured, the colours ranging from red, through orange, yellow, green, blue, and indigo, to violet. The colours blend imperceptibly into one another, so that it is impossible to say exactly where one stops and the next begins, and at either end they shade off so that it is difficult to say just where the band ends. This coloured band is the celebrated spectrum of white light revealed by Newton. Any particular point in the spectrum corresponds to light that has been bent through a certain angle from its original direction. Now, if we take a certain beam coming out of the prism, say the centre of the yellow, and pass it through a second exactly similar prism, it will be bent aside, or deviated, as the physicist prefers to call it, through exactly the same angle as the particular coloured light was deviated by the first prism: the same holds for a third prism, or any number of prisms. White light, then, contains in itself an infinite variety of different kinds of light, each of which is characterized by being bent through a certain angle by a given prism. To fix the deviation we have to specify the glass of which the prism is made, because different glasses have different powers of bending light; we must also name the angle of the prism, since a prism with an angle of sixty degrees bends a given kind of light more than a prism of thirty degrees does.

While we can, by virtue of our colour sense, distinguish lights differently bent by their different colours, it is clear that the amount of deviation is a more precise way of indicating the kind of light we mean than a mention of the colour is, for lights that are bent by amounts only slightly different appear the same colour to the eye, and also it is not always easy to state exactly what colour a given light is: a greenish blue, for instance, will be called blue by some, green by others. The deviation of light in its passage from one substance to another—e.g. from air to glass—is called refraction by physicists, and the property of being deviated is called refrangibility, so that we can summarize what has been said so far by saying that white light contains light of all degrees of refrangibility between certain limits, and that a certain refrangibility may be attributed to every simple and pure light—that is, to every light that cannot be split up into other lights by its passage through a prism.

To have discovered all this was one of the great achievements of Sir Isaac Newton. To-day we can go a step further back, and say, in more general terms, what it is that really characterizes a monochromatic light, or light of one colour, meaning by colour that exact position in the spectrum given by the refrangibility. We know that light has the properties of a wave motion, and that lights of different colours are distinguished from one another by different frequencies of vibration, the frequency of the extreme visible violet being very nearly twice that of the extreme visible red. This fact is sometimes expressed by saying that the visible spectrum contains one octave of colour, since in sound a note that has twice the frequency of another note is called the octave above it. If, therefore, we want to indicate a particular green light, bent just so much by a given prism, and therefore occupying a precise place in the spectrum, we can specify its frequency, which relieves us of the need for speaking of the kind of glass and the angle of the prism. The frequency is the distinguishing number of a pure light, just as it is the distinguishing number of a pure note.

In empty space light of all colours has the same speed, namely 186,326 miles a second, which is more conveniently remembered as almost exactly 300,000 kilometres a second. Now during the time of one complete vibration a wave motion must advance through a distance of exactly one wave-length, so that if we multiply wave-length by frequency (the number of vibrations in a second) we have the distance through which the wave passes in one second, or the velocity. To give the frequency, then, is the same thing as giving the wave-length in empty space (which is very nearly the same as the wave-length in air, since the presence of the air retards the light but little). In solid and liquid substances, say glass or water, however, light travels markedly more slowly than in space,[1] and each particular colour travels with a different speed—in fact, it is the difference of speed that leads to the difference of refrangibility. The wave-length of light is therefore different in different substances, but the frequency is everywhere the same. With visible light the frequency is extremely high, and the wave-length correspondingly small. For a particular yellow light produced when salt is brought into a colourless gas-flame, for instance, the wave-length in air is .0000589 centimetre, and the frequency 509,100,000,000,000 vibrations per second! Since the velocity of wireless waves is the same as that of light, we can at once calculate the wave-length if we are given the kilocycles, or number of thousand vibrations, a second. An ordinary frequency for wireless waves is 1,000 kilocycles, which means a wave-length of 300 metres.[2]

---

[1] Light has in ordinary glass about two-thirds of the speed which it has in empty space, in water about three-quarters.

[2] 1,000 kilocycles = 1,000,000 vibrations a second and 300 metres = .3 kilometre; .3 × 1,000,000 = 300,000 kilometres a second, the velocity of light.

The periodic or wave nature of light is revealed to us by what is named the interference and the diffraction of light. Let us consider first of all interference, in terms of water ripples. Suppose that we have, hung over the middle of a smooth pond, a spiral spring carrying at its lower end a horizontal rod, bent down vertically at each end so that the extremities, a yard apart, say, nearly touch the water. If the spring is made to vibrate up and down, the two ends of the rod will dip in and out of the water together and cause two series of ripples running out in ever-increasing circles from centres a yard apart. The crests will always leave the centres together in perfect time, since the same movement of the rod gives rise to both series. We ask now what will happen when the two series of ripples overlap. If we choose any point on the pond's surface, the water there will be pushed up and down by each ripple just as if the other were not there, and to find out the movement we must add the movements due to the two separate ripples. According to the position of the point, it may happen that the movements are exactly in step, when the motion will be just twice as violent as that due to the ripple from one centre alone, or they may be exactly out of step, so that the crest of one ripple system always arrives at the same time as the trough of the other. In this case the two will exactly annul one another, and at this particular point the water will move neither up nor down but will be always at rest. We say that the waves interfere. Clearly, if the point selected is at the same distance from each centre, then the waves will be in step at that point, and therefore we have violent motion all along the line which passes just between the two centres, and is at right-angles to the line joining them. Again, if the point selected is farther from one centre than the other by exactly one wave-length, then the crests will arrive together at this point, only one system will be a wave behind the other, which makes no difference to what happens, just as, if we see two men running together round a corner, we can only say that they have run an equal distance, or that one is a whole lap, or two whole laps, or any number of whole laps behind the other. There will therefore be a series of lines (actually slightly curved lines) on the surface of the pond on which the motion is violent. Midway between these there will be the points at which one ripple system is exactly half a wave-length behind the other, giving rise to lines along which there is no motion at all. Thus the surface of the pond will be streaked with strips of vigorous wave motion and strips where there is little or no motion. No energy is, of course, destroyed by the interference of the two systems of ripples, but it is removed from some places and heaped up in other places—it is redistributed. If, opposite the two centres, we half immerse a vertical board in the pond, then at some points of the board the water will wash up and down, while at others, in between them, the water will not move. If we pull the board out of the water we shall have a wavy edge to the wet part. Measuring on the board the distance apart of the places where the water was still, and knowing the distance of the board from the centres and the distance apart of the centres, we can easily calculate the wave-length of the ripples.

We have devoted some little consideration to this ripple case because the interference of waves which it illustrates is of extraordinary importance in the study of vibrations. It is quite easy to obtain interference of sound waves: if we strike a tuning-fork and, holding it near the ear, turn it round, keeping it vertical all the time, certain positions will be found for which no sound is heard, while in intermediate positions the sound is vigorous, although the distance of the fork from the ear is the same all the time. This means that for certain positions of the fork the distances are such that the sound waves from the two prongs interfere at the ear. By slipping a cardboard tube over one of the prongs, and so cutting off its contribution, the sound will be restored to vigour. We have the paradox that we increase the sound—at a particular point—by cutting off part of it!

Let us now turn to the real object of our study at the moment, the interference of light. The only difficulty is to hit on some way of getting two sources of light in which the vibrations are in step, for that condition is necessary to start with. In the pond case we kept the ripples exactly together at the centres where they were produced by governing them with the same spring. In the tuning-fork case the prongs look after themselves, and swing together without any trouble. If we put two slits in front of a flame, however, the beams coming from the two will come from different parts of the flame, and so be quite unconnected from the start, and we should have no right to expect interference. We can, however, make use of reflection, which gives us an exact picture of any light: the light and its image in the mirror then supply us with two light sources in which the vibrations of each little part of the one must be exactly in tune with the vibrations of the corresponding part of the other. Or, again, by reflection from two mirrors we can obtain two images of the same light, which two images must be exactly similar to one another in the smallest detail. We now see how to start two light waves spreading out in all directions from two different sources, so that at the sources they are exactly in step. We are also in a position to consider the simple cases of interference of light which confront us in daily life.

A thin film, say a film of oil on water, has two surfaces, and light from any bright spot, say one particular point of the sky or of a bright cloud, must be reflected from both surfaces into our eye, placed in a suitable position. Of the two beams which enter the eye, one from the top and the other from the bottom surface of the thin sheet of oil, one has gone a little further than the other, owing to the thickness of the film. For a certain wave-length this extra distance will be just an odd number of half wave-lengths, and therefore any light of this particular wave-length will cancel out at our eye by interference. White light, such as the sky, light we have considered, contains, as we have seen, a great range of wave-lengths: the effect of the film will be to cancel out one particular kind of light and weaken all in its neighbourhood, and therefore we shall see a coloured film, coloured because, if we remove certain colours from white, the remaining colours no longer make white, but blend to a new tint. For instance, if red is removed from white we get peacock blue. Which particular colour cancels out depends upon the thickness of the film, and the angle at which the light comes from it, since the smaller the angle which the arriving light makes with the surface of the film, the longer the difference of path caused by reflection at the two surfaces. All these facts can be verified with ease either with a flat soap film, obtained by dipping a ring of wire into a soap solution, or with a film of oil such as can be observed lying on water on the road after rain. The oil film will appear differently coloured at different parts owing to its irregular thickness, the changes of colour succeeding one another closely near the edge, where the film tails off quickly into nothing. If the eye be moved the colour at any particular spot changes. The flat soap film is particularly interesting, because if it be arranged vertically it will drain away, so as to be very thin above, and thicker below, and a glorious series of horizontal bands of colour will be seen. The colours of the ordinary soap bubble, of thin slivers of mica seen at the edge of a broken piece, of a thin film of air pressed between two really flat pieces of glass, or between a slightly rounded lens surface and a flat glass, of the thin films of fat sometimes found in cooked meat, of the bubbly scum on ponds are all due to interference, and bear silent witness to the wave theory of light.

The colours of thin films are remarkable not only for their beauty and for their scientific importance: they have considerable practical application. If we have one true surface and place another glass surface upon it, any irregularity of the second surface will make itself visible by an irregularity of the colour patches produced by interference from the two glass surfaces. The places where the air film between the two surfaces is irregular in thickness can then be marked, and the surface worked by hand until, when placed on the test surface, or 'optical flat' as it is called, the colour is uniformly spread. The highest class of optical mirrors and lenses for scientific purposes, such as microscope lenses, are finished in this way, and many delicate measurements can be made by interpreting the message of the light waves about film thicknesses.

If we start with a bright slit of light together with its image in a mirror we have two exactly similar sources of light, and the effect is exactly that illustrated by our example of the pond: where the light from the two falls on a screen, we have, alternatively, places where the wave motion is violent and places where it is negligible —in other words, a series of light and dark bands, the so-called interference fringes. These interference fringes play a most important part in the measurements of the physics laboratory. Their virtue is that they give a most delicate method of detecting small changes in length. The existence of a bright band at a particular spot tells us that the difference of the distances from the two light sources to that spot is exactly a whole number of wave-lengths, or, fixing for simplicity the central bright band, that the distance from the centre of that band to the two sources is exactly equal. If by any means we slightly change the length of one of the light paths, even by a distance which is only a fraction of a wave-length of light, say by a hundred-thousandth of an inch or so, then the position of the band will clearly shift to a new position from which the distances *are* equal. If a billiard-cue had a perfectly flat end, and were stood on this base, a sheet of paper pushed under one side would make the point of the cue move through quite a large distance, and in the same way a very small change in one light path makes the point at which the two paths meet in tune swing through a comparatively large distance, which is detected as a movement of the fringes.

How can we alter the distance of one of the light paths without altering the other? In the most famous instrument for this purpose, the interferometer, as it is called, which we owe to Professor Michelson, the light from a slit falls on a plate of glass placed at 45 degrees to its path; part of the light is reflected off at right-angles to its original path, while part passes on through the glass. By a suitable arrangement of mirrors, which turn them back upon themselves, the two beams are brought together again, and produce interference fringes, since only at one point will the two paths be exactly equal. For most of their path, be it noted, the two beams will have been travelling at right-angles to one another. We can alter one path independently of the other by slightly moving the mirror which reflects it back. Clearly, this instrument provides us with an extraordinarily sensitive way of measuring lengths. It was used in the attempt to measure the earth's velocity through the ether, which became famous as the starting-point of Einstein's special theory of relativity. We will now briefly consider the reasoning which led to this attempt, and the method employed in the experiment.

Towards the end of the nineteenth century, the belief was general that all space was filled by some subtle substance which conveyed from place to place the wave motion which we call light, or, more precisely, light was supposed to be a wave motion propagated through this imaginary substance as sound waves are propagated through a solid. This hypothetical substance was called the luminiferous ether. Some men of science took the view that you could not have a wave motion without something for it to travel through, but that, as we knew nothing about it except that light travelled through it, the ether was little more than a subject for the verb 'to undulate.' Others considered that it had the physical properties of an elastic solid, and were inclined to try to work out an elasticity and a density for it. All were agreed on this point: that if the ether had any kind of reality it should be possible to measure the speed with which our earth was passing through it. If we could do this the ether would give us some absolute standard of rest, and we could speak of a velocity measured with respect to the ether as an absolute velocity, in contrast to velocities with reference to other heavenly bodies which is all that we can measure at present, without being able to say that any star is at rest rather than any other star.

The method proposed for measuring the speed of the earth through the ether depended upon this principle: that if light travelled through a stationary ether, and the earth was likewise moving, though with a much smaller velocity, through this ether, then a light signal sent out in the direction of the earth's motion and reflected back to its starting-point would take a little longer than a signal sent out at right-angles to the direction of the earth's motion and reflected back again, both paths being of equal length. The difference of duration of the two journeys would enable us to calculate the speed of the earth through the ether. It is usual to make this clear by the illustration of a man rowing on a broad river, say a mile wide, flowing steadily in one direction. If he rows down the river from one mile post on the bank to the next, and then back again, clearly the river will help him in one direction and oppose him in the other, but nevertheless he will take longer over this double journey than he will to row across the river and back again along a path at right-angles to the direction of flow. The reason is clear: he does the journey downstream with a speed obtained by adding the speed of the current to his own rowing speed, and does it quickly, being therefore *helped* by the current during a comparatively *short* time. On the way back he is opposed by the current, and takes a long time over the journey, being *hindered* during a *long* time. Taking an extreme example, supposing his speed on still water is four miles an hour, and that the river current is three miles an hour, he will go downstream at seven miles an hour past the bank, and will do his mile in one seventh instead of one quarter, of an hour: on his way back, however, he will have a speed of only one mile an hour past the bank, and will take a full hour, instead of one quarter, the total journey occupying an hour and a seventh instead of half an hour on still water. The journey across is also somewhat lengthened by the current, but to a lesser degree; in our particular example it will take about three-quarters of an hour instead of the half-hour in still water. If the rower had no other way of measuring the speed of the river, he could, then, clearly do it by timing himself for the two different journeys and comparing the results, knowing only his speed on still water.

In the ether case the velocity of the earth is very small compared to that of light, so that the effect to be expected from the earth's motion would be exceedingly minute—a difference of about one part in a hundred million. This is where the delicacy of the interferometer is essential. Suppose that we can set it up so that one of the two light paths, which lie at right-angles to one another, is in the direction of the earth's motion through the ether. Interference fringes will be formed. If we now rotate the whole apparatus through a right-angle the other light path becomes the one in the direction of the earth's motion, and will be the one in which the light is retarded, so that there should be a shift of the fringes if there is any difference of the speed of the light in the two directions. This is the essence of the famous Michelson-Morley experiment, carried out originally in 1887 with the greatest care and skill, and since repeated many times. In one of the repetitions, by Professors Morley and Miller, the lengths of the light paths were, by repeated reflections, made as great as 32 metres each (about 35 yards), which length contains 55 million waves of the yellow light used, so that the change of path to be expected from the earth's motion (one in a hundred million) amounts to over half a wave-length, which is doubled because turning through a right-angle interchanges the paths. There should, therefore, have been a shift of over a whole interference fringe, and less than a hundredth of this can be measured. When we think that the actual duration of the whole light path of thirty-odd metres is a ten-millionth of a second, that the difference of time on the two paths for which we are looking is a hundred-millionth of this, and that we can measure an effect less than a hundredth of this, the power of the interferometer needs no further emphasis.

The result of the Michelson-Morley experiment is negative: no effect of the earth's motion through a hypothetical ether on the speed of light has ever been established. It is true that in 1925 an announcement by Miller that he had obtained a very small effect created a sensation in the world of physics, but he has obtained no further confirmation, and since then two other American experimenters, R. J. Kennedy and K. K. Illingworth, working independently at Pasadena, have made exceedingly careful repetitions of the experiment, with different apparatus, and have obtained no effect whatever. Quite recently Michelson himself has announced that new experiments of his own likewise show no effect. No motion of the earth through the ether can, therefore, be detected, and this means that there cannot be an ether with the properties of any material body. It was to explain this extraordinary effect that Einstein originally devised the theory of relativity, which involves as a fundamental feature this impossibility of measuring any motion through space by means of light signals. No matter with what speed or in what direction the experimenter be moving, he will always find the same result for the velocity of light. The velocity of light is one of the most fundamental quantities in the whole of physics, and has been measured to an extraordinary degree of accuracy. Michelson has during the last few years been making new measurements, and as a result of these announces the velocity of light to be 299,796 kilometres a second, with a possible error of one kilometre only!

A second field of usefulness of the interferometer is a more practical one—namely its application to the measurement of the standard of length, which arose from the difficulty of making sure that any distance between scratches on a metal bar has the degree of permanence which is required. The length of the bar changes with temperature, but that, of course, can be avoided by making the comparison with the standard always at the same temperature. The length of a metal bar, however, tends to change with age, owing to very slow internal rearrangements of the molecules, and, although by great care in the preparation and keeping of the bar these changes can certainly be made exceedingly small, there is still a little uneasiness in the scientific heart at the thought of depending for our standard on any particular bar of metal, rather than on something in Nature that does not change, something that is always at hand whatever happens to any particular piece of stuff. Originally it was proposed that the earth itself should be taken as our standard, the French metre being defined, when it was legally established in 1800, as one ten-millionth of the distance from pole to equator measured along a meridian, which it very nearly is. This distance, however, cannot be determined accurately enough for our requirements in the matter of standards of length today. After much discussion it was proposed to use as the standard of length the wave-length of a certain very pure light given out by cadmium: this element is chosen because the wave-length of certain of its spectral lines is particularly definite, not a mixture of closely neighbouring wave-lengths. The cadmium atom, which is the same at all times and in all parts of the world, is thus made the final appeal, but, as a wave-length of light is not the kind of thing an engineer can handle, and is not a very convenient thing even for the physicist who wants to measure a length, the problem arises of finding just how many of these wave-lengths there are in whatever bar we have been taking as our standard. We can then check from time to time if the bar is still exactly the same length, and, what is equally important, we can check standard bars in different parts of the world against the standard wave-length provided by the cadmium atom. By the skilful application of Michelson's interferometer the length of the standard metre at Paris was determined in terms of the cadmium wave-length, and we now know that the distance between the scratches on the precious bar contains 1,553,163.5 wave-lengths of red cadmium light (in air at standard temperature and pressure). This result is certainly correct to within one part in a million.[1] Strange as it may appear, therefore, if anyone asks as to where our final appeal lies in matters of length, we point to the light coming from a special kind of electric lamp containing cadmium vapour.

The interferometer is also applied to find out the minute faults of expensive lenses. Here, then, is an instrument which has led to the theory of relativity, helped to establish a standard of length, and aided in the perfecting of photographic lenses. Behind it all lies the wave theory of light, and the magnificent regularity of its behaviour gives us confidence in our belief that light has the periodic properties of a wave motion.

---

[1] The repetition of the measurement of the metre in terms of cadmium light made, with a different form of apparatus, by MM. Benoit, Fabry, and Perot gave 1,553,164.13, differing from Michelson's value by 1 part in 2,400,000 only !

FINDING THE SIZE OF A STAR

A sensational application of the interference properties which light possesses has given us the first measurement of the diameter of a star. Although many stars, the so-called 'giants,' are immensely larger than the sun, they are so far off that even with the largest telescope they appear mere points of light, and show no disc whose diameter can be measured. Suppose, now, that we consider light from a single very distant point to fall on two mirrors suitably arranged, and the light from the two mirrors to be brought together by a system of lenses, it is clear from what has been said that interference fringes, alternate light and dark bands, will be produced. The larger the separation of the mirrors the narrower the fringes. Now consider what happens to the light received, by the same system of mirrors and lenses, from a distant point very near the first distant point. A system of interference fringes will likewise be formed, but a little to one side compared to the first set. If the two distant points are separated by a certain amount the bright parts of the fringes due to one will fall on the dark parts of the fringes due to the other, and no fringes will be visible. The wave-length of light being exceedingly small, a simple calculation shows that, if the mirrors which receive the light from the two points are separated by a distance of some feet, then the angle made by lines drawn from the two points to the eye of the observer needs only to be exceedingly small for the fringes to vanish.

It may be added, as an item of information, that, other measurements having shown the distance of Betelgeuse to be about 930 million million miles, we conclude that the diameter of the star is something over 200 million miles, or, in other words, if the centre of the star were placed at the centre of our sun, the orbit of our earth would fall right inside the star, which would, in fact, nearly fill the whole orbit of Mars.

Another aspect of the wave theory now demands our attention. We know that sound waves can turn round corners: a brick wall, for instance, does not cast a sharp sound shadow where it ends, but rather its shielding action is incomplete until we have advanced far into its shelter. In the same way the ripples on the surface of a pond will spread somewhat behind any plank or such like body placed in the way. If, then, it is a property of waves to bend round the edges of obstacles, how is it that light casts a sharp shadow, and will apparently not turn round corners? The answer is that the amount of bending at sharp angles depends upon the wave-length, being greater the greater the wave-length: that with light, owing to the small wave-length, it is very small, that it emphatically does exist, and that a narrow source of light is found *not* to cast a sharp shadow at a straight edge when the matter is carefully investigated, but rather forms a series of very fine alternate dark and light bands parallel to the edge, which are known as diffraction fringes, the bending being technically called diffraction.

If the amount of bending does, in fact, depend upon the wave-length, we shall expect it to be different for different coloured lights, so that when white light grazes an edge there should be a separation of the prismatic colours at the edge of the shadow. This also is found to be true, the red light, which has the longest wave-length, being the most bent, and the violet least. The general fact can be easily verified by looking at the bright filaments of an electric lamp through a fine cambric handkerchief, when each wire will be seen to be surrounded by a series of coloured fringes. It is upon this phenomenon that systematic measurements of the wave-length of light, especially of spectral lines, are based. The light from a fine slit is passed through a glass plate ruled, by means of a diamond point, very closely with parallel lines. Such a plate is called a diffraction grating, and must be adjusted so that the lines are parallel to the slit. The ruled lines, which are actually rough grooves, are comparatively opaque, so that what we really have is a series of very fine clear slits. The light is turned through an angle which depends upon the wave-length, and also upon the distance between the lines: with the kind of dimensions which are used, namely about 15,000 lines to the inch, the bending is very large. The measurement of the angle of bending is carefully made, and from it the wave-length is deduced.

The theory of diffraction is a little complicated, and what is attempted here is only the roughest indication as to what is in question. The ruling of the gratings is a matter calling for the highest technical skill, and good gratings are very much prized and command high prices. Rowlands of Baltimore devoted many years to their production, and in the course of his labours made great improvements in the accurate cutting of screws. So, in physics, one thing leads to another.

What, then, is the general lesson of the interference and diffraction observations which, as we have seen, occupy so large a part in modern physics? It is that, whatever light may be, it is something which passes through empty space with a perfectly definite velocity, and produces effects which show that it must have the alternating or periodic properties of waves.

So far we have been talking about light visible to the human eye. However, just as there are air vibrations which are not audible, such as those caused by a plank oscillating two or three times a second, or, at the other extreme, the ultra-sonic vibrations, similarly there are vibrations of the same nature as ordinary light which are not perceived by the eye. Beyond the violet there are shorter waves (or, putting it the other way, vibrations of higher frequency) which have a strong effect upon the photographic plate, and are known as ultra-violet rays. These are often depicted in popular literature as violet streamers, but, of course, as they cannot be seen they have no colour—they are not violet, but *beyond* the violet. There are many different kinds of ultra-violet light, just as there are many different kinds of visible light, corresponding to different frequencies. The frequencies just higher than the visible violet pass through the glass of ordinary window-panes and camera lenses: they have a strong action on photographic plates. When somewhat higher frequencies are in question the rays do not pass through ordinary glass, although special glasses are made which transmit them. The rays which produce sunburn are of a very narrow range of ultra-violet light of wave-length in the neighbourhood of three hundred-thousandths of a centimetre, as compared with the four or more hundred-thousandths of a centimetre which are the shortest violet waves visible. These rays not only do not pass through ordinary window glass, but they are markedly absorbed by the atmosphere, so much so that in winter, when the sunlight has, on account of its obliquity, to traverse a greater thickness of atmosphere than it does in summer, practically none of them gets through. This is why it is that even intense winter sunlight does not produce tan and sunburn. Shorter waves still are absorbed in smaller thicknesses of air, but can be photographed with special plates and quartz lenses, quartz being a material that is very transparent to the ultra-violet rays. These different properties of different kinds of ultra-violet light show us how careful doctors treating patients with the light must be.

Passing still further into the short-wave region, we come to waves which are absorbed even by a fraction of an inch of air, and can only be photographed with very special methods and apparatus pumped free of air. When, however, we come to waves shorter than three millionths of a centimetre the penetration begins to increase: we are approaching the X-ray region. For one of the most striking discoveries of the present century is that X-rays are of the same nature as ordinary light, their peculiar properties being a consequence of an exceedingly short wave-length. The wave nature of X-rays has been proved in the same way as the wave nature of light—by making use of a 'grating' of regularly spaced lines. The structure of X-rays is, however, so fine, the wave-length is so short, that the ruled gratings by which the wave-length of light is measured are altogether too widely spaced for efficient service. It was the discovery of the German physicist Laue that in crystals, in which the atoms are spaced in regular rows, we have a diffraction grating, ruled by Nature, suitable for demonstrating and measuring the wave-length of the X-rays. This discovery was speedily extended by Sir William Bragg and his son, Professor W. L. Bragg, who have showed how, conversely, X-rays may be made to yield the most far-reaching information as to the structure of the crystals. It should, perhaps, be mentioned that quite recently it has been found possible to use artificially ruled gratings to produce results with X-rays in certain extreme cases.

The X-rays used by doctors for diagnosis have wave-lengths of a few thousand millionths of a centimetre, while those used for curative purposes are shorter still. Finally, one class of rays from radium has the same properties as X-rays, but is of still shorter wave-length: these rays, the so-called gamma rays, have, in extreme cases, wave-lengths of less than a ten-thousand-millionth of a centimetre.

The gamma rays represent the very shortest wave-lengths of which we can handle a source in the laboratory. They are at the same time the most penetrating: even after they have passed through a plate of lead ten inches thick the effect of the gamma rays from radium and its products can still be detected. Of recent years, however, much evidence has been collected to show that even more penetrating rays, originating outside our earth, come through the atmosphere and penetrate some yards into the earth or water. The experimental difficulty is to distinguish between these rays and the gamma rays due to the radium which exists in the earth itself; the effects are very small, and require to be carefully disentangled. However, by sending up balloons, carrying delicate instruments to detect the rays, and by sinking instruments below the surface in deep lakes formed from snow-water, the existence of this class of radiation has been definitely established. The balloons show that the radiation increases in strength as we proceed to great heights, which is what we should expect for a radiation coming from outside, since it has less air to traverse at high altitudes, whereas a radiation originating in the earth should become correspondingly weaker as we go upwards. The snow-water contains no matter of mineral origin, and so cannot contain traces of radium producing gamma rays; measurements show that the effect decreases as we sink the instruments into the water, which again argues a radiation coming from outside. The radiation can be detected some fifteen yards below the surface, which points to a very penetrating nature indeed; ordinary X-rays would only penetrate a foot or two of water at most.

It was at first suggested that the penetrating radiations probably came from the sun, but the discovery that there is no difference in the radiation by day and by night soon put this explanation out of court. It is now generally accepted that the rays come from outer space, and accordingly they are called *cosmic rays*. From their penetrating nature we argue that the wave-length must be considerably less than that of the gamma rays; the exact value deduced depends upon the nature of the mathematical argument, but it is probably somewhere round about a million-millionth of an inch—the waves are more than ten million times shorter than the waves of ordinary light, which in their turn are some hundreds of million times shorter than ordinary wireless waves. If the whole world, together with its wireless stations and their waves, were reduced in size until it was no bigger than a grain of dust, the diminished wireless waves would still be a hundred thousand times as long as the cosmic rays.

The origin of these cosmic rays, which form the short wave-length limit of our 'electromagnetic spectrum,' is still in doubt, but it seems probable that they are the result of the building up of atoms in remote regions of outer space, or, as Millikan poetically puts it, that the rays are the birth-shrieks of atoms. A brief reference to this aspect of the subject will be found in Chapter VII.

So much for the short wave-length side of things. At the other end of the spectrum, beyond the visible red, lie invisible infra-red rays, which can be detected by their heating effects. A kettle of boiling water in a dark room gives out no visible light, but if it be hung up and the hand be placed at a little distance underneath it (so as not to be affected by the hot air rising from it) a heat will be felt which is due to invisible radiations. The infra-red radiations do not affect ordinary photographic plates, but special plates which are sensitive to them can be made, and, as a matter of fact, a kettle has been photographed in a perfectly dark room by the invisible heat radiations which it gives off. Of course, ordinary light radiations, if strong enough, also produce a distinct heating effect: with sunlight the greatest heating effect lies in the visible yellow. With the infra-red radiations, however, the heating effect assumes particular prominence because it is the property by which they are most easily detected. The heating effect of the ultra-violet rays, in the intensity in which they ordinarily occur, is much too small to be conveniently measured, but it also must exist.

At still longer wave-lengths we come to the type of electro-magnetic waves which are produced in wireless telegraphy. In practice these are usually of wave-lengths which are measured in hundreds of yards, but as a laboratory curiosity wave-lengths of a small fraction of an inch can be produced. We can say, then, that, using the term 'light' in the most general sense, we have a spectrum stretching without a break (for all gaps have recently been bridged) from wave-lengths of hundreds of yards down to less than a ten-thousand-millionth of an inch, of which vast range only a very small region is visible to the eye. Calling an octave a band of radiation stretching from a given frequency to double that frequency, we may say that our complete spectrum consists of sixty octaves, of which only one is visible.

What are the properties which all these waves have in common? The characteristic wave effects of interference and diffraction have been demonstrated with the shortest X-rays by making use of the regularities of crystal structure, the natural even spacing of the atoms in a crystal taking, for these short waves, the place of the artificial ruled gratings used with ordinary light. With ultra-violet waves ruled gratings can be used, with thousands of lines to the inch, while for long infra-red waves reflection methods have been employed to demonstrate interference. More remarkable still, Professor E. V. Appleton has recently made use of the Heaviside layer to demonstrate directly the wave nature of wireless waves, or, rather, since the wave nature was already clear from other evidence, it would be better to say that he has used it to demonstrate the existence of the layer. His experiments show exactly the same effects as those produced by ordinary light, on an enormous scale. The Heaviside layer just mentioned is a sheet of atmosphere, some seventy miles up, which has peculiar electrical properties which make it act as a mirror for wireless waves. The waves reflected from the layer have travelled farther than those which proceed from the same source along the ground, and if the difference of path is half a wave-length, or a multiple of this, just the same kind of interference takes place as was described for ordinary light, only here the wave-lengths are measured in hundreds of yards instead of in millionths of an inch. The size of the interference fringes is correspondingly great. This interference of direct and reflected wireless wave is responsible for many of the peculiarities of short-distance wireless transmission known as 'fading.' It is cited here merely to show the generality of the ideas of modern physics, and how the principles established in one branch of the study turn up unexpectedly, often with great practical importance, in another part of the field.

All the different kinds of 'light' waves have the same velocity in empty space, which suggests a common nature. They are, in fact, all what is known as electro-magnetic waves. The thing that varies periodically is the electric force at right-angles to the direction in which the wave is travelling: accompanying the variations of electric force we must necessarily have fluctuations of magnetic force, also at right-angles to the direction in which the wave is travelling, and at right-angles to the electric force. Thus, if a wave is travelling across the page from left to right, there will be an electric force in the direction from top to bottom of the page, say, which first points up and then points down, diminishing smoothly to nothing and then growing in the opposite direction in the course of each oscillation, while the magnetic force will be at right-angles to the sheet of paper, and will likewise fluctuate. It is therefore better to speak of our general spectrum as the spectrum of electro-magnetic waves, ordinary light being an electro-magnetic wave with a particular range of wave-length.

If this is so, we should expect to be able to demonstrate experimentally electrical and magnetic effects with ordinary light. Long ago, Faraday, the prince of experimenters, who was convinced, by that instinct for truth which he possessed ('He smells the truth,' said a great German scientist of him), that there was a connection of this kind, showed that a magnetic field exerted a certain effect on light passing through heavy glass. This effect, known as the rotation of the plane of polarization, is somewhat too complex to explain in a short sketch of this kind. Likewise we can only cite the effect named after Zeeman, who discovered that the light from a source placed in a strong magnetic field was modified in a peculiar way as compared to light from the same source without the magnetic field. There is, however, a connection between light and electricity, the general nature of which is simply understood, and which has, moreover, assumed the greatest importance of recent years. It is called the photo-electric effect, and has interesting practical applications as well as deep theoretical significance.

The photo-electric effect occurs when light of short wave-length falls on a clean metal surface, say a plate of carefully polished zinc. The plate then loses negative electricity, and becomes positively charged. It has been proved by many experiments that what actually happens is that electrons, little atoms of negative electricity whose nature is discussed in the next chapter, are made to issue from the metal by the influence of the light. The stronger the light, the more electrons come from the plate every second. If the inside of an evacuated glass bulb be coated with a suitable metal (for some metals, such as potassium and rubidium, are much more sensitive in this respect than others), and a wire protruding into the bulb be provided to conduct the electrons away as they are freed, a small current can be obtained which indicates the strength of the light. Such photo-electric cells, as they are called, are widely used in connection with television and talking films, for by their aid fluctuations in light can be turned into fluctuations of electric current, which in their turn can be converted into sound, as in the ordinary telephone. If, then, to take the case of the speaking film, sound can be made to cause fluctuations of light, which is easily done by the aid of a thin plate which responds to the sound, a band of light and dark alternations due to speech or music can be printed on the side of the film. The particular way in which the lights and darks at any place follow and shade into one another will correspond to a particular sound. When it is desired to reproduce the sound this band is run in the path of a beam of light, which accordingly fluctuates in a way corresponding to the original sound, and the light, falling on a photo-electric cell, is then made to govern a sound producing mechanism of some kind in the way just indicated.

The number of electrons liberated is, however, only one aspect of the question ; another is the speed, or energy, with which the electrons come out of the metal. Strangely enough, this is not influenced at all by the strength of the light, but only by the frequency. Blue light liberates electrons of small energy of motion; violet light produces electrons of somewhat greater energy; ultra-violet light causes the emission of faster electrons still; while with X-rays the electrons expelled have a still greater energy. The energy which is imparted to the electrons before they leave the metal is, in fact, proportional to the frequency of the light. This is a very fundamental and important fact for modern physics.

Let us look at it from another point of view. Suppose that we make electrons hit a piece of metal with a given energy, which we can do by liberating electrons from a hot wire, as we do in the ordinary wireless valve, and then speeding them up with an electric field, just as, in the old game of bat, trap, and ball, we first make the ball jump from the trap and then slam it with the bat. When the electrons strike a metal plate X-rays are produced. The whole process must be carried out in a highly exhausted tube, so that there are very few air molecules present to get in the way of the flying electrons and make them lose their speed: such a tube is an X-ray tube, as used in hospitals. If, by using a great voltage, we make the electron fly very fast, and hit the metal with great energy, very penetrating X-rays ('hard' X-rays, as the doctors call them) are produced—that is, waves of very small wave-length and high frequency. If the electrons strike the metal with less energy the X-rays produced are of longer wave-length, and smaller frequency. Suppose, again, that we send a stream of electrons which, by comparison, are very slow and have small energy, through a gas, then we produce waves which are so much longer than X-rays that they are visible light: this is what happens in the tube with the pink glow used in advertisement signs, the neon tube. In each case sending a greater number of electrons does not alter the frequency of the waves produced, but merely produces more of them: we get a brighter light. It is as if, in sound, the note of a gong should depend upon the violence with which we struck it a blow, being higher the more violent the blow, while the strength of the sound depended upon the number of blows. The whole point is that, apparently, the energy which is needed to produce a *single* train of waves of any kind of 'light' depends upon the frequency of the light produced, while if a single train of light waves produces an electron from an atom the energy of that electron depends upon the frequency of the light. This queer fact lies at the basis of the quantum theory, which is discussed in Chapter VI. It is introduced here merely to show that there are certain aspects of light which are not of the kind which can be explained from the simple wave theory, for this theory alone would not lead us to suppose any relation between the frequency of a single set of waves and its energy.

There are other electrical effects of light which are receiving great practical application to-day. If light falls on a film of the element selenium, prepared in a certain way, the resistance of the selenium to electricity is diminished, and hence, if we have the selenium joined up with a battery, a bigger current flows, which can be magnified as much as we like by the technique of wireless valves. If the light is made to fluctuate the current will fluctuate in a corresponding way, so that clearly we can use a selenium cell to turn light, made to vary in the proper way, into speech, just as we can use a photo-electric cell. There are many other practical uses of the selenium cell. In some parts of London the street lights are turned on automatically by the aid of selenium cells: as soon as daylight fails the resistance of the cell goes up, and the change of current is made to operate a switch. Burglar alarms can clearly be operated on the same principle: as soon as light is made in a dark room a bell rings. These tricks are all very interesting, but for our present purpose the great thing to be noticed is that light, visible and invisible, is a manifestation of electric force which produces obvious electrical effects.

The study of light, then, like so many other parts of physics, seems to be the study of energy, the study of waves, and the study of electricity. There are three interconnected aspects of the same thing. At one time we fix our main attention on one, at another time on another, but they cannot be considered independently. If we understood fully any one part of physics, we should understand all.

CHAPTER V

ABOUT ELECTRICITY AND MAGNETISM

THE word electricity derives from the Greek *electron*, amber, for it was known in classical times that amber, when rubbed, acquires the property of attracting light bodies, such as morsels of straw or scraps of feather. We say to-day that the amber becomes charged with electricity, and we know that if we support any body, say a metal plate, on an insulating stand we can communicate part of the charge to it by simply touching it with the electrified amber. If we hang up two light balls by silk threads, which do not conduct electricity, and charge them each by means of a piece of electrified amber (or sealing-wax or glass, for these bodies, and many others, become electrified when rubbed), they will repel one another if brought close together, so that we say that two electric charges of the same kind exert a force of repulsion on one another. It is found, however, that if a rod of sealing-wax is rubbed with a woollen cloth, and then used to charge a small ball with electricity, while a second ball is charged with a glass rod which has been suitably rubbed, the two balls then attract one another. This shows that there must be two different kinds of electricity, for, taking a charged ball, we can, by choosing a suitable substance, charge a second ball either so that it attracts, or so that it repels the first ball. If the two balls be charged with the same kind of electricity, either glass or sealing-wax electricity (to call them so for the moment), they repel one another; if they be charged with different kinds of electricity they attract one another. The two different kinds of electricity are always generated when a body is electrified by rubbing, for if the body, say a glass rod, acquires a charge of the one kind, the cloth acquires a charge of the other kind, and, as can easily be shown by experiment, in equal quantity. The process of rubbing does not then, on the whole, produce electricity, but separates out the two kinds in quantities just sufficient to neutralize one another completely if they are brought together again.

The two kinds of electricity, distinguished by the sense of the force which they exert on one another, are always spoken of as positive and negative electricity, glass electricity being called positive and sealing-wax electricity negative. There is no particular reason for this choice, any more than there is for the names chosen to represent political parties, for instance, but, once the arbitrary choice has been made, we stick to it.

It is familiar to everybody that when we join the poles of an electric battery of any kind, say an accumulator, by a metal wire, an electric current flows through the wire. By this we mean that the wire acquires special properties: it exerts a force on a magnet brought into its neighbourhood, it grows warm (if the wire is a very good conductor the heating effect is small, but nevertheless exists: if the wire has a high resistance the heating is very obvious, as in an electric lamp or electric radiator), and, further, if the wire be cut, and plates attached to each end, and these plates be then immersed in a solution of metal salts, a chemical action takes place, as exemplified by the separation out of the metal in the familiar silver or nickel plating baths. We therefore say that an electric current has a heating, a magnetic, and a chemical effect. In the old days it was customary to distinguish between the current electricity produced by a cell, and frictional electricity produced by rubbing a glassy or resinous substance: they were spoken of as different things and called voltaic electricity and static electricity. We know now that all the properties of an electric current are produced by an electric charge in motion, as has been shown by rapidly whirling a charged body. Electric currents are merely moving charges, just as water currents are merely moving drops. The moisture in a sponge and the liquid in a river are the same thing, water, but the properties which a river has of turning a mill wheel, wearing away the bank and so on, are consequences of the motion. In the same way electricity in motion produces effects which stationary electricity cannot. Exactly how the electric charges pass along the wire we do not yet know, or, as the man of science would say, the mechanism of metallic conduction of electricity is still obscure.

There is a very close connection between electricity and magnetism. Just as there are two kinds of electric charge, there are two kinds of magnetic pole. One end of an ordinary bar magnet will always tend to point north, the other south. Two south-seeking poles or two north-seeking poles repel one another: a north and a south pole attract one another. This is merely a general analogy between electricity and magnetism, and does not in itself show any real connection between the two. But there is an actual interaction; in the first place an electric current, that is a motion of electric charges, creates a magnetic force in its neighbourhood. This is a very familiar fact, of which the simple galvanometer, consisting of a pivoted or suspended magnetic needle surrounded by a coil of wire, carrying the current to be measured, is a good illustration. The strength of the magnetic force is used to measure the strength of the current. Another familiar example is the electromagnet, in which the magnetic force produced by the current is used to convert the iron core into a magnet. But not only does a moving electric charge produce a magnetic force: a moving magnetic pole produces an electric force, which can cause a current to flow in any circuit of wires in the neighbourhood.

This electro-magnetic induction, as it is called, discovered by Faraday, is involved in practically every important bit of electrical apparatus. In a dynamo an electric current is generated by turning coils of wire in a magnetic field, which comes to the same thing as moving a magnet towards fixed coils of wire. The changing magnetic field may itself be produced by a changing current, which will therefore generate or induce, as it is called, a changing current in a neighbouring circuit with which the first current is not connected; but it must be clearly understood that a steady current produces a steady magnetic force, and so cannot induce a current in another circuit near by. The induction of one current by another is utilized in the telephone, in wireless telegraphy, and in countless electrical devices. We have, then, the general rule that any movement of electric charge creates a magnetic force, and that any movement of a magnetic pole creates an electric force. It was by giving to these ideas mathematical form, and extending them from conducting wires to empty space, where electric and magnetic forces exist apart from any matter, that Clerk Maxwell came to the conclusion that if at any place we can produce oscillations of electric force (which must, of course, from what has been said, be accompanied by oscillations of magnetic force) these oscillations will produce electro-magnetic waves which will travel out across empty space with the speed of light. This prediction was, as is well known, speedily realized by Heinrich Hertz, who demonstrated experimentally the existence of 'wireless' waves. Every generator of such waves is merely an apparatus for making electric charges rush backwards and forwards with a given frequency of oscillation in the wires of the sender, just as every source of sound is a vibrating material body. The moving charge has, as it were, a grip on what, for want of a better term, we call the ether of space, and sends out its waves through this ether: the vibrating string or fork is in contact with the air, and sends out sound waves through it; and we can give a still more obvious illustration of both cases by a man shaking one end of a long cord up and down, with the result that a series of humps, or waves, chase one another along the cord.

The general rules which govern the behaviour of electric charges towards one another, and the interconnection of electric and magnetic forces, do not, however, tell us anything about the ultimate nature of the electric charge, which, as far as they are concerned, might be something in the nature of a subtle fluid obeying certain mathematical rules—the 'electric fluid' of which old writers used to speak. Nowadays we know that such a term conveys a false impression. The natural unit of electric charge, the electron, the discovery of which transformed physics and ushered in the modern period, was revealed by the study of the passage of electricity, not through wires, but through the very attenuated gas in an exhausted tube.

Suppose two rods of metal sealed through the walls and protruding into the interior of a glass tube: these rods may or may not terminate in plates of different shapes, according to the particular purpose of the tube, but in any case they are called electrodes. As long as the air inside the tube is at the pressure of the atmosphere, quite a high potential difference, say 10,000 volts, can be applied to the electrodes without any spark passing. If now the air be gradually pumped out a stage is soon reached at which the electric discharge sets in, first as a thick, furry-looking spark, and then as a beautiful glow, filling the tube with a sequence of striking and significant appearances which have been carefully studied, but must not detain us here. When at length the air in the tube has been reduced to somewhere about a ten-thousandth of the original amount, the glass of the tube shines with a characteristic bright green glow. By introducing into the tube little screens of different shape it is easy to show that this glow is due to something streaming from the negative electrode, or cathode, as it is called, which strikes the glass walls. We cannot see the stream, but the glow which it produces enables us to follow the movement. If a magnet be brought near, the stream is turned from its path, just as an electric current in a very flexible wire would be, for since, as we have described, a current produces a magnetic force, a magnet must produce a force on a current. A plate charged with electricity also turns the cathode stream aside, again just as if the stream consisted of a number of little charges.

A study of the joint action of the electric and the magnetic force leads to the conclusion that the cathode stream consists of a swarm of *negatively* charged particles, and, further, gives the mass of each particle, if we know its charge, which we cannot find without further experiment. This further experiment, which will be described in a moment, supplies information which enables us to find both charge and mass. It turns out that the charge is exactly the same as the smallest charge which we find associated with an atom of matter when we pass a current through a liquid, and drive the charged atoms across, as we do, for instance, in electro-plating, which really consists in employing an electric force to push charged atoms of metal contained in the plating bath out of the solution on to the article to be plated. No experiment has ever led to the discovery of any smaller charge, and, further, no matter what gas we have in the tube, the amount of charge on the particles in the cathode stream is always the same. This ultimate unit of *negative* charge it is which we call the electron. Its mass is exceedingly small, even in a world of littles: it is, for instance, but little more than a two-thousandth of the mass of the smallest and lightest atom, the atom of hydrogen. The electron is not a tiny piece of something material carrying an electric charge, it is an electric charge pure and simple, just as a raindrop is just water. We are accustomed to find water contained in vessels, and electric charges sitting on matter, but the electron and the raindrop are divorced from containers. That it has any mass at all is another way of expressing the fact that it requires a force to set an electric charge in motion, as can be mathematically demonstrated.

The cathode stream in the exhausted tube is only one way of producing electrons from matter: what actually happens in the tube is that the positively charged atoms in it are banged against the cathode by the electric force applied, and knock electrons from it and from themselves. There are various secondary actions which, in the actual tube, complicate the appearance of things. Electrons can also be made to come out of any piece of metal by heating it: a red-hot poker held near a charged electroscope will discharge it. The object of the glowing wire in the familiar electric valve of wireless is to produce a supply of electrons. Light or X-rays falling on a metal plate will also drive electrons from it, as mentioned in the last chapter. In short, maltreating an atom, either by banging it hard by other atoms, as we do when we increase the heat agitation, or shaking it violently by changes of electric force, or hitting it hard with a moving electron, will make it yield up electrons. It can be shown by experiment that the electrons produced by one method are the same in all respects as those produced by another method, and not, as might be imagined, that one kind of electron comes from one metal and another kind from another metal. Whatever the source, whatever the method of production, the same quantity of electricity constitutes this minute unit of negative charge. How minute the charge is can be, perhaps, best described by stating that to carry the kind of current that flows through an ordinary electric lamp would require the passage of a million million million electrons every second. The ordinary small 50-ampere-hour accumulator stores a charge equal to that on a million million million million electrons. So small is the atom of electricity.

A positive charge *not associated with matter* has never been found. When an electron is driven right out of a single atom (which is normally electrically neutral) the remaining part of the atom, having lost a little negative electricity, is positively charged. Positive charge has not, then, the absolute character of negative electricity in that it cannot be obtained free from matter: the appearance of its characteristic properties follows a loss of negative electricity, just as nakedness is an inevitable sequel of loss of clothes. Whereas we can have a coat and a shirt apart from a man, we cannot have half-nakedness, which attends the absence of these vestments, apart from a man. We can have negative electricity in an isolated state, but we can only have positive electricity in the form of a positively charged atom, or an assembly of such atoms. Since the hydrogen atom is the lightest atom, the lightest unit of positive electricity which we can have is a hydrogen atom which has lost an electron. This particular atom only has one electron to lose, as is further discussed in our Chapter VII.

When X-rays, for instance, pass through a gas, such as air, they shake electrons from many of the gaseous atoms, and produce an assembly of positively charged atoms and electrons, the electrons, in general, being picked up by other atoms which then have an electron too many, and are negatively charged. X-rays, then, and also other agents, such as swiftly moving electrons or other particles, create in a gas a swarm of positively and negatively charged atoms or molecules, such charged particles being called ions, or 'goers,' because they travel when an electric force is applied. Now charged particles of all kinds have a remarkable property, which they share with dust particles: they act as centres of condensation for the moisture in the atmosphere. The atmosphere may have more moisture in it than it likes to hold: if there is nothing for actual tiny drops to form on they do not appear, and the air remains clear, though super-saturated, as it is called, with moisture. If dust particles, or charged atoms, or electrons are present, then each one acts as a chair on which the water can sit, and a fog of droplets is formed. The dust in the atmosphere and the ions formed by the ultra-violet light in the upper atmosphere, play a great part in the rainfall. It is quite easy to produce an artificial cloud in the laboratory by passing X-rays through air containing more than its load of moisture, and such clouds, in one form or another, have found a prominent place in modern physics. For one thing, they furnish the means of measuring the charge on the electron to which reference has already been made. The formation of a drop round a negatively charged particle gives us a method of counting the particles, for the size of the minute drops can be estimated from the rate, a very slow one, at which the cloud settles,[1] and the total amount of water in the cloud can be obtained by weighing. The total charge on the cloud can be measured electrically. By a device the cloud can be formed on the negative particles only. It is clear that we can thus obtain information enough to calculate the charge on one negative particle—that is, the charge on one electron. More recently Millikan has made the most accurate measurement of the charge on the electron by microscopic observation of the behaviour not of a cloud of droplets, but of a single charged droplet about a ten-thousandth of an inch in radius.

The property which charged particles have of acting as centres of foggy condensation has been made by C. T. R. Wilson the basis of one of the most ingenious and sensational experiments in modern physics. When an atom of helium discharged by a radio-active

---

[1] The clouds of the sky are, of course, subject to gravity and are falling all the time, but they consist of such small drops that, owing to the air resistance, the rate of fall is exceedingly slow, and in general they turn to rain before they reach the ground as cloud.

element, say the particular element called Radium C, dashes through the air, which it does with a speed of about 12,500 miles a second, it knocks electrons out of the atoms wholesale, and leaves a litter of charged atoms along its path. Its path, like the path of a miniature tornado, is marked by a track of destruction, and our problem is to render the track visible. If the air, or for that matter any other gas, through which the rays are passing, is damp (or contains saturated water vapour, to use the more precise expression), and is then cooled by a slight expansion, part of the moisture wants to deposit, and utilizes the charged atoms or molecules as starting-points on which to build drops, just as a lady might use small sticks as centres on which to wind pieces of wool. The result is that the path of the swift atom, the so-called alpha particle, shot out by the Radium C, is marked by a thin white line of fog, looking, against the black background which is provided, like a line drawn by a finely pointed white chalk. The line actually consists of a string of tiny droplets. Swift electrons also produce charged particles along their paths, by knocking electrons out of the atoms which they meet, so that their paths are also made visible by this method. Since X-rays also throw electrons out of atoms with considerable energy, as we mentioned when discussing the photo-electric effect, the path of a narrow beam of X-rays is marked, not by a single straight line, but by a tangle of white lines, each line being due to swift electrons released by the X-rays, each of which produces a track of its own. These tracks can be photographed and studied at leisure. The actual time of passage through the apparatus of the atom, electron, or X-ray whose effects are thus studied is, speaking generally, a thousand millionth of a second or so; it is the damage which it leaves behind it that is utilized by the moisture and permanently recorded. Some of the striking results which follow from C. T. R. Wilson's method are mentioned in Chapter VII.

Electricity is, then, like matter, granular in structure: the atom of electricity is the tiny unit of negative electricity called the electron. All electrical phenomena ultimately come down to the behaviour of the electrons, either singly or in swarms, but we are still very much in the dark about many aspects of the way in which electrons behave inside matter, although we have a great deal of information as to their manners and customs when free. The generation of wireless waves at a broadcasting station, for instance, is a matter of encouraging a mass-migration of electrons first in one direction and then in the other, tens of thousands of times a second, in the wires of the aerials. The electrons are the little handles, so to speak, by which we have a grip on the ether, and can shake it, so as to produce the waves in it. We do not know, however, the kind of way in which the single electrons behave in the wire when a current passes through it—how far they go, or by what path among the atoms. At present the wire is for us like an underground railway to a man observing a city from a balloon: he can see a swarm of people entering it at certain stations, and count them, and others coming out at other stations, but how they get along, and which people are reappearing at which places is beyond his observation.

The glow in discharge tubes, such as the neon lamp now sold commercially, is a matter of the passage of electrons through gases, of which we know more than we do of the passage of electrons through metals. X-rays, as we have seen, are generated when swiftly moving electrons are suddenly stopped by hitting the heavy atoms of a metal (platinum, or molybdenum or tungsten) plate in an exhausted tube: this gives our ether handles a very sudden jerk and starts a sharp pulse of waves. The study of any feature of the electric discharge in exhausted tubes or of the flames of the electric arc light brings us at once to a consideration of the behaviour of the electrons present. The liberation of electrons by a hot wire, and their subsequent control by the electric field between this wire and the 'grid,' is the essential function of the wireless valve. The liberation of electrons in the upper atmosphere by radiations from the sun is the fundamental cause of the Heaviside layer, of the aurora borealis, and other phenomena of atmospheric electricity. The electron is the key to modern physics.

We know that a current flowing round a circuit produces a magnetic field. A charge of electricity in motion is the same thing as a current, so that an electron moving round in an orbit of any kind will create a minute magnetic force, and be equivalent to a tiny magnet. The general magnetic properties of all substances can be explained, in fact, in terms of electrons circulating in the body of the substance, which respond to magnetic fields. The only substances which are popularly thought of as magnetic are iron and steel, but, in fact, all substances have magnetic properties. The elements cobalt and nickel possess the same magnetic properties as iron in a marked, if less, degree, and are said to be ferro-magnetic (*ferrum* is the Latin for iron). The other elements are so much less magnetic than iron that it requires very delicate measurement to show their magnetic properties. With some of them, the so-called para-magnetic substances, this slight magnetism is of the same kind as iron, so that, for instance, a piece of the substance, if exposed to a magnet, will try to approach it and move to the place where the magnetic force is the strongest; but others, the so-called dia-magnetic substances, have opposite magnetic properties, in that they try to move to the place where the magnetic field is weak. They are repelled by the pole of an ordinary magnet, instead of being attracted in the way to which we are accustomed with iron.

The most important features of these different classes of magnetic behaviour are accounted for by the theory of electron orbits. There are, however, many characteristic properties of magnetism which are still obscure. One of the most striking facts is that magnetism is not a property of the elements present in an alloy, but depends in some mysterious fashion upon the way in which they act upon one another when juxtaposed in the solid state. For instance, alloys can be prepared which contain as much as eighty-eight per cent. of iron and yet are not at all magnetic, while other alloys, the Heusler bronzes, which contain only metals which themselves are very feebly magnetic, namely manganese, copper, and aluminium, are nearly as magnetic as iron. The important and characteristic magnetic properties of the various special steels, such as chromium steel, prepared nowadays cannot be calculated from the magnetic properties of the substances they contain. Magnetism, then, does not depend in general upon the kind of atoms present, but upon the way in which they are arranged in a crystalline structure within the substance—crystalline structure, because every metal and alloy consists of a mass of minute crystals. It is even true that the magnetic properties of one and the same substance depend markedly upon its crystalline structure, which can be influenced by heat treatment. Manganese steel, for instance, is tough, ductile and non-magnetic if it is tempered by being heated and quenched in cold water: it is hard and magnetic if heated and allowed to cool slowly. The electron orbits in question must take up their characteristic form and position under the influence of the internal forces which govern the crystal structure of the substance. When it is said that the general magnetic properties can be explained by the electron orbits, what is meant is that the way in which temperature and other circumstances affect the properties can be explained, but we still do not know why, for instance, ordinary iron should be so characteristically magnetic: we do know that it is *not* due to any property possessed by iron atoms under all conditions, for, besides the facts already quoted, certain chemical compounds of iron, such as iron carbonyl, have the opposite properties to iron, and are dia-magnetic. When we know something more about the electron orbits in solids, and how they are influenced by neighbouring atoms, we shall, no doubt, understand this. At present, however, it is one of the most intriguing problems in modern physics.

CHAPTER VI

ABOUT THE QUANTUM THEORY

MANY of the most exciting of the recent developments of physics have been bound up with investigations of the properties of the radiations which travel through empty space, and, in particular, with their relationship to matter. Radiations, of which visible light is an example, are always started on their voyage by some kind of minute electrical disturbance in matter, and their arrival on matter of any kind is always attended by electrical effects. Sometimes these electrical effects can easily be detected, as, for instance, the induction effects of the wireless waves of broadcasting, which are primarily electrical before they are converted into sound; the ionizing effect of X-rays on the gases through which they pass; or the photoelectric effect of ultra-violet light. In other cases, as in the passage of light through glass or water, there is no electrical effect of this obvious kind, although the action of a magnetic field on the light during its passage shows clearly what we should have expected from other considerations—that electrical forces are in play. Through the common friend, electricity, the behaviour of radiation is inextricably mixed with the properties of matter; and the quantum theory, which is a theory of radiation initiated at the very beginning of the present century by Professor Max Planck, has made its influence felt in every branch of physics.

To approach the theory we have to consider the question of the energy of radiation rather more closely than we have done hitherto, and, in particular, we have to make ourselves familiar with something known to physicists as a 'black body,' which plays an important part in many questions of radiation. In the first place, however, it must be pointed out that surfaces which absorb radiation well send out the same radiation plentifully themselves if they are heated, while bodies that do not absorb well radiate very poorly themselves. For instance, soot or any dull black surface absorbs practically all the radiation which falls on it, as is clearly the case with visible light, while bright tin, which reflects so well, can clearly absorb very little. If, now, two vessels of exactly the same size and shape—say quart kettles—be taken, one of iron which is covered with soot, and the other of bright tin, and boiling water be poured into each, the water in the sooty kettle will grow cold quicker than that in the other kettle, because more energy is radiated away by the black surface. Similarly, the best vacuum flasks, for keeping hot liquids hot and cold liquids cold, are always silvered: if the flask contains cold liquid, we have the advantage that the silver reflects radiation falling on it from outside, or, in other words, absorbs very little radiant heat, while, if the flask contains hot liquid, we have the advantage that the hot silver radiates very badly, so that very little of the heat is lost by radiation. The ideal 'black body' of the physicist is one that absorbs completely every kind of radiation falling on it, and so must, if heated, radiate as much of every kind of radiation as possible, more than any other kind of body at the same temperature would radiate. Of course, we cannot coat a body with soot to make a 'black body' of this kind, for the soot would burn off when the body was strongly heated. Certain metal oxides are black, and also resist heating, and so can be used to prepare a black surface, but theory shows that the best way to realise the ideal 'black body' is to make a closed vessel of some heat-resisting material—of, say, iron, or, if higher temperatures are needed, of special porcelain—heat the vessel strongly from outside, and let the radiation come out from the inside of the closed vessel through a small hole. In a general way it can easily be seen why this acts as a 'black body.' A perfect absorber becomes, if hot, a perfect radiator. A small hole in a hollow vessel, especially if the interior of the vessel be blackened, acts as a very good absorber, for the radiation which passes through the hole gets scattered about inside and never comes out again. For instance, an open window in a white house-front looks a perfectly black square on a sunshiny day: the sunshine is reflected from the white wall, which looks bright, but, passing through the hole on to the room, is weakened at every encounter with objects there, and very little escapes again out of the window. The glowing heart of a furnace is an ideal radiator, for it is practically a small hollow surrounded by glowing bodies all at one high temperature.

The paradox of the term 'black body' appears when we consider what happens when we heat the walls of our iron vessel red hot, or even white hot. A bright light comes out of the hole, and yet we call this 'black body radiation.' All that is meant is that it is the kind of radiation which comes from a body that, since it absorbs all radiation that falls on it, presumably sends out, when heated, as much radiation of every kind as possible. The term 'complete radiation' or 'full radiation' probably expresses to the layman more clearly what is meant, but the term 'black body radiation' is so widely used—and gives rise to so much misunderstanding—that this word of explanation has been offered.

Some very interesting questions arise in connection with the radiation from a full radiator, or black body. Since we have in such a hot body a source of radiation which has no prejudice in favour of any particular kind of light, red, green, blue, or invisible, since it absorbs all equally, we should like to know how it distributes its energy among the different possible wave-lengths, for that would clearly tell us something about the relation between matter and radiation, just as, if one had a completely unprejudiced Chancellor of the Exchequer, the way in which he distributed money to the different State activities—so much to the armed services, so much for education, and so on—would tell us much about the relation between money and the State.[1] When experiments are made, it is found that at every particular temperature the hot body sends out a whole range of wave-lengths, a whole spectrum. When the body is very hot—white hot—it radiates sufficient to be seen of every kind of light in the visible spectrum: when it is only moderately hot—say at the temperature of boiling water—it does not give out any visible light (a boiling kettle is not visible in a dark room), but nevertheless it does give out radiation, of the infra-red kind. There is a perfectly simple rule by which to understand the general nature of the changes in radiation that take place as the body is heated: the hotter the body the more the short wave-lengths predominate. Thus a poker at the temperature of boiling water is invisible in the dark: all its radiation is in the infra-red. When it is heated, the boundary of the radiation creeps towards the red, until, when it is about 500 degrees Centigrade, some visible red is included, and the poker is feebly red hot. As it is

---

[1] The analogy is not a very good one, because every Chancellor of the Exchequer, unprejudiced or not, is a black body who absorbs fully all the radiation, that is, money, that comes his way, however differently he may radiate it.

heated still more, more visible rays are added to the spectrum of the radiation, and the poker appears orange and then yellow hot, and, finally, even a little blue is sent out along with the other rays, and the poker is white hot. All the time most of the energy is in the infra-red, but the place of greatest energy tends to approach the visible spectrum. A poker is not, strictly speaking, a 'black body,' but behaves sufficiently closely to one to illustrate our point. A body as hot as the sun gives out *most* radiant energy at a place in the visible spectrum: a body immensely hotter would give it out in the blue, or, if hotter still, in the ultra-violet.

Careful measurements made with full radiators in the laboratory show exactly how much radiant energy of each wave-length is sent out at different temperatures: at any one temperature they furnish a kind of census of the number of units of energy of given wave-length, just as a population census furnishes, for any one country, the number of people of each given age. Different countries, where the distribution is different, correspond to different temperatures. Now, before the quantum theory was put forward, there was no idea of natural units of radiant energy; it was believed that we could have any amount of energy, as small as we pleased, radiated by a hot body or a luminous atom. It could be shown mathematically that, if this were true, we should expect a hot body to radiate all its energy in the violet and ultra-violet end of the spectrum, which we know to be untrue. No theory based on the older ideas gave any proper account of the radiation of the unprejudiced 'black body,' which became, at the end of the past century, the bugbear of the physicist.

The problem was solved in the first year of the present century, when Planck showed that, to get the right result, it was necessary to make a revolutionary hypothesis: that radiant energy is sent out in packets, as it were, in units or atoms of energy, just as matter exists in atoms. We cannot have less than an atom of lead, say; any minute piece of lead must consist of a whole number of atoms. We cannot have an electric charge of less than an electron. In the same way, we cannot have less than a unit—or quantum, as it is called—of radiant energy, and any body that sends out or absorbs radiation must deal with one or a whole number of quanta. Radiant energy is dealt with in grains, not in infinitely divisible quantities.

The little parcel of light of one wave-length in which radiant energy is delivered is sometimes called a 'light dart,' sometimes a photon. The photon is simply a quantum of radiant energy, the only object of sometimes using the new term being that 'quantum' is a more inclusive term, which can be applied to other things as well as light—for instance, to the vibration of whole atoms and molecules.

The quantum of radiant energy differs from the quantum of electricity, the electron, in a very important way. The amount of charge is the same on all electrons: there is but one unit. This unit of radiant energy, however, is different for every different kind—that is, for every different wave-length—of radiation. It is, in fact, proportional to the frequency, so that the quantum of energy of extreme visible red radiation is only half that of the extreme visible violet radiation, which, as we have said before, has double the frequency. The quantum of an X-radiation is very much greater than the quantum of any visible radiation. It is as if we could only buy things in fixed quantities, but that the minimum quantity varied with different things: pumpkins by the pennyworth, peaches by the shilling's-worth, gold rings by the pound's worth, diamonds by the five pounds' worth. The unit of price increasing as the size of the article diminishes, corresponds to the quantum of radiant energy increasing as the wave-length diminishes.

Light, then, or radiation in general, has a packet property as well as a wave property, and this is one of the paradoxes of modern physics. Newton's conception of light was a stream of particles, which he endowed with something in the nature of pulsating properties in an attempt to account for certain phenomena which we can now easily explain on the wave theory. If white light contained particles of all sizes, corresponding to all the different colours (or wave-lengths, as we now say) which it contains, it would be fairly easy to imagine the amount of energy in each particle to depend upon its size, and the quantum, or atomic, nature of the energy would be a natural consequence. To account for what we observe to-day, however, we have to suppose that light behaves under some conditions as a stream of particles, each of which has a fixed energy, and under others, described in Chapter IV., a wave motion. All that can be said in excuse is that we know by experience just when to treat it as a wave motion to get the right results, and when to treat it as a quantum, just as the weather-wise know when to take out an umbrella and when to take a light hat. It would be more satisfactory to be able to adapt a uniform line of conduct, but it is not in general practicable, although at the present time an advance is being made towards a scheme by which all matter has wave properties, and the wave and quantum properties of radiation are reconciled. The new theory, called the method of wave-mechanics, receives further mention in Chapter VII.

If the question of 'black body radiation,' which led to the quantum theory, were the only place where the need for it was felt, then the theory might be kept in the background, and only trotted out on special occasions. There is, however, a whole series of important observations in different parts of physics that seem to demand the quantum theory naturally. Take, first of all, the photo-electric effect. We have seen that, when light or any radiation of short wave-length falls on a metal, electrons are shot off, the *number* depending on the strength of the light, but the *speed* on the kind of light. If the radiation is done up in packets of energy, and the energy can be expended in pushing out electrons, then clearly we should expect each atom of light either to throw out an electron with a definite speed, or to do nothing, but not to throw out an electron with some lesser speed. According to the quantum theory, a short wave-length—that is, a high-frequency radiation—should therefore throw out electrons of speed much higher than that of those ejected by radiation of long wave-length. This is just what is observed: red light does not eject electrons at all, violet light shakes them out with a small speed, ultra-violet light produces greater speed, and X-rays throw out very fast electrons. Red light, the quanta of which are very small on account of its low frequency, has no effect, because a certain minimum energy is required just to jerk an electron out of an atom; the energy of the red quanta is less than this minimum. Allowing for the small energy required just to free the electron, the energy which the electron acquires can be shown experimentally to be exactly proportional to the frequency of the radiation. This is now so well established that, in cases where it is difficult to measure the frequency of very short ultra-violet waves by ordinary means, the energy of the electrons which they eject from matter has been determined, and taken as a measure of the wave-length. The same method has been applied to the exceedingly high-frequency gamma rays of radium.

The quantum theory is applied, not only to radiation, but to any atomic process that has periodic properties, or, in other words, that repeats itself with a frequency of so many times a second. The spinning of an atom or molecule round an axis, like a top, is such a property. According to the quantum theory, a spinning body can only revolve at certain speeds, and, in particular, cannot revolve very slowly—it can either not spin at all, or must spin at the first permitted speed; just as, if all we demanded of a clock was that it should show twelve o'clock at mid-day, it might either be stopped, or the hour hand might revolve once, twice, three times, or any whole number of times in twenty-four hours, but not at any intermediate speed. The consequence of this extraordinary restrictive law is that, if we have a gas at low temperature, where the molecules collide with one another comparatively gently, it is only occasionally that one will spin at all, the blows generally experienced not being sufficient to give a molecule the slowest spin permitted. The consequence is that to raise the temperature of the gas we do not have to give much more than the energy required to make the molecules rush about more vigorously. At higher temperatures, however, where the motion is more vigorous, the collisions are sufficiently vigorous to spin most of the molecules at the least rate allowed by the quantum theory, and in consequence we have to supply energy, not only to make the molecules hustle along their paths, but also to spin them. This would indicate that it requires less heat to raise the temperature of a gas one degree if it is cold than to raise it by the same step of temperature if it is hot. This is, in fact, what we find by experiment to be the case.

This effect is even more pronounced with solid bodies. The result of two different methods of calculation which apply the quantum theory to the vibrations of a solid is the same, namely, that to warm a body when it is exceedingly cold requires next to no heat compared to that required to warm it by the same amount when it is hot. This is in accordance with the striking experiments mentioned in Chapter II., which have shown that, in actual fact, the quantity of heat which raises a pound of copper, say, by one degree when the copper is at ordinary room temperature, will raise the same pound of copper by more than 20 degrees if we start at 250 degrees Centigrade below the melting-point of ice. The agreement between observed fact and the predictions of the quantum theory is very close when the consequences of the theory are worked out in detail.

Wherever we find atomic or molecular oscillations of any kind, the quantum theory holds sway. Within the atom we have electrons tracing out orbits which repeat themselves in a general way with certain definite frequencies: as we shall see in the next chapter, the quantum theory accounts for the kind of light they give out. In gases, the molecules spin round and round as well as rush to and fro: the quantum theory not only explains the response of the atoms to heat, but also to light. The spins, or oscillations, of ordinary visible bodies—tops and fly-wheels and projectiles—are, however, not affected by the quantum theory, since the behaviour of the single atoms is not here in question, any more than the atomic theory appears in the weight of such bodies. The weight can only vary in steps, since we cannot have any smaller weight than that of one atom, but these steps are very much too small to be noticeable when we are dealing with bodies composed of millions of millions of millions of millions of atoms, and we appear to be able to change our weight at will in a continuous manner. In the same way, quantum spins are very much too small to make themselves felt in any engineering problems, or they would have been detected long ago.

The quantum theory is typical of modern physics, in that it is a case where a special mechanics is applied to atomic processes. In the physics of the past century, now known as 'classical physics,' atoms were always treated as minute bodies, obeying the ordinary laws of mechanics which have been found to govern the behaviour of objects of ordinary size—or macroscopic objects, as they are often called, in contrast to microscopic, or sub-microscopic, objects. Radiations were supposed to be waves in a special subtle medium, the ether, it is true, but their properties were deduced by analogies drawn from the behaviour of such waves and vibrations as can be actually seen or detected in real media, such as air, or water, or solids. To-day, the results of our experiments have forced us to the conclusions that the laws of motion of atoms and of their parts, and the rules governing the radiations which they send out and absorb, are in many respects of a special kind which can only be found out by trial and repeated comparison with the phenomena themselves. There never was, after all, any reason to suppose that the behaviour of the parts of an atom should obey the same rules of mechanics as the parts of a machine, or as the parts of a solar system, any more than there is any warrant for supposing that the psychology of a crowd reflects that of the individuals composing the crowd. It must, of course, ultimately be possible to work out the behaviour of matter in bulk from the behaviour of the individual atoms, once we know their laws; and of radiation in bulk from the properties of the packets, or quanta, of radiation, although we have found that the reverse—the deduction of the behaviour of the tiny units from that of the bulk—is not possible. At present, however, it is simplest to remember that matter in weighable lumps, and radiations as ordinarily detected, obey the 'classical' laws of mechanics, electricity, and optics, while, for processes concerning single atoms and their little parcels of radiation, special laws hold, of which the quantum theory embodies some of the most important.

CHAPTER VII

ABOUT THE ATOM

Having now taken a brief glance at the subject matter of physics, and considered some of the results of the intense work, in laboratory and study, of the last thirty years, we now come to treat of the atom, which is in itself the epitome of that work. To consider the nature of heat it was sufficient, for our purpose, to treat atoms and molecules as little units of matter which are in continual agitated motion. When the generation of light, and of radiation in general, is in question, we must, however, go further, and inquire about the structure of the atom itself, which is also deeply involved in modern considerations of electricity. In the older chemistry, atoms were taken as little unbreakable particles endowed with certain forces of chemical attraction or 'affinities': to-day chemical theory is more and more finding its expression in terms of the detailed structure of the atom, and, in particular, of the electrical forces whose nature is fixed by that structure. Even in the science of heat certain of the finer details require us to cease to regard the atom or the molecule as a mere particle, and to invoke the information as to atomic structure which has been recently won. The further the study of this structure is pushed, the wider becomes the field in which it is seen to be applicable, and the more chemistry and physics tend to become two closely allied branches of one science.

Up to the close of the nineteenth century, the accepted view was that matter consisted of atoms, but that to every element corresponded a different kind of atom, which had nothing in common with the atom of any other element. All atoms were supposed to be unbreakable, indestructible, and of the same nature all through, like a jelly, and not patchy like a currant pudding—homogeneous, as the man of science prefers to say. Professor Clerk Maxwell, the greatest theoretical physicist of his time, called them 'manufactured articles,' meaning that once they were made in the beginning they persevered unchipped and unchanged through all time. It is true that more than a hundred years ago the chemist Prout had suggested that all atoms might be structures built of hydrogen atoms, but this supposition had been dismissed because accurate determinations of comparative atomic weights showed that the weights of the different atoms were not a whole number of times the weight of the hydrogen atom—chlorine, for instance, has atomic weight 35.46 and not exactly 35 or 36, as Prout's theory would lead one to suppose, the weight of the hydrogen atom being 1.

The idea that atoms might have parts arose again round about the beginning of the present century, when thus provides us with a stream of minute atomic projectiles with which we can test the properties of matter. Rutherford's experiments were directed to find out how such flying particles were scattered by atoms put in their way. He found out that while most of them were but little turned aside from their original path by a gold leaf, or other metal foil, which they traversed, yet occasionally a particle was deviated through a very large angle, even, in extreme cases, coming out of the foil again on the same side by which it entered.

To appreciate the deductions to be made from this, let us suppose a man firing rifle bullets through a wooden wall. The bullets will be a little turned from their path by irregularities in the wood, but will proceed on the whole much in the original direction. If now, the rifleman finds that occasionally a bullet is turned aside through an angle of fifty or sixty degrees say, that every now and again one comes back and nearly strikes him, he can only conclude one thing—that the wooden wall contains small lumps of iron, or other comparatively impenetrable substance, which are struck, more or less directly, from time to time, and register their presence on the path of the projectiles. In the same way, Rutherford concluded that his experiments showed that atoms must contain small impenetrable centres capable of turning the swift alpha particles aside through large angles. Calculation showed that every alpha particle must pass right through hundreds of atoms in traversing the foil, so that the small deflection of the average particle must merely be the result of a number of tiny disturbances, but calculation shows equally that it is beyond all probability that the very large deflections can be made up of such small pushes, chancing to occur all in the same direction. In experiments of this nature general reasoning is far from being sufficient; everything must be controlled by precise mathematical computation of the size of the effect to be expected, and a comparison with the quantities measured in the experiment.

The agreement of Rutherford's results with the calculations made on the supposition that atoms contain repellant cores, as it were, which turn aside any alpha particle which happens to strike or come near to any one of them, was sufficient to convince the scientific world of the truth of his conception of atomic structure. His experiments were carried out by putting in the path of the alpha particles which had passed through the foil a little screen of a phosphorescent material: when a particle strikes this material its energy is sufficient to produce a tiny scintillation of light, which can be observed through a microscope. By this method only the position of the arrival of the particle is registered, not its whole path. Luckily, C. T. R. Wilson has given us a way, described in Chapter V., of registering the path of an alpha particle through a gas, by depositing tiny drops of moisture on the atoms which it deranges in its path. Photographs of the tracks of alpha particles show that, while most of them are only slightly bent, every now and then one is violently turned from its path at a sharp angle, while at this angle another track leads off, so that the path appears to fork into two prongs. One of these prongs is the path of the particle itself, deviated by striking the nucleus of an atom of the gas: the other prong is the track of the nucleus, which is struck so hard a blow that it itself rushes through the gas, producing a similar effect in its passage to that of the particle itself. The number of forks in a given number of tracks, and the angles of the prongs, agree closely with what Rutherford's theory leads us to expect. We can, then, in this way photograph the tracks and collisions of particles so small that a million million of them side by side would only extend over a fraction of an inch, and so light that a million million million of them would not weigh as much as a grain of dust. We detect them by taking advantage of their tell-tale electrical effects.

These different experiments, then, show that within the atom there must exist some very minute centre of force, comparatively massive so as not to be brushed aside by the flying particle—a stone in the atomic plum. This is not, perhaps, a very good comparison, for the atomic stone, or nucleus, as it is called, has a diameter only about a ten thousandth of that of the atom, but it has practically all the mass of the atom. The nucleus is positively charged, so that it neutralizes electrically the negatively charged electrons which make up the rest of the atom. It is in virtue of its high charge of positive electricity that the nucleus can turn aside the very swift alpha particle through a large angle. As its charge is of opposite kind to the electricity of the electrons it attracts them, but they do not fall into it, any more than the planets fall into the attracting sun: in both cases the motion of the lighter body round the more massive central body provides a tendency to fly off which just counterbalances the attraction. The atom is, in fact, a kind of solar system, except that, whereas the planets that circulate round the sun are all roughly in one plane, the orbits of the electrons that circulate round the nucleus have, in a heavy atom, where there are plenty of them, planes which lie in many different directions.

Before we pass on, let us consider the general picture which we must now form of an atom. At the centre we have a nucleus which, if we magnify it a million million times, will be about the size of a pea. It must not, of course, be thought of as a definite body like a small pea, but rather as a centre of electric force pervading the surrounding space. What we mean by the size is that, when we approach from outside the boundary which takes the place of a surface, the force suddenly becomes very great. If we had a very strong fire nobody would approach nearer to it than a certain distance: this would mark out a kind of limit, though there would be no actual wall there. It is in this sense that we speak of a boundary and a size for the nucleus. Around this nucleus clusters a swarm of electrons, moving in orbits, some closer, others further out, the number and arrangement depending on the kind of atom. In the case of the heaviest atoms there are about ninety of them. These electrons occupy a space which, when magnified like the nucleus a million million times, would be about a hundred yards across. They occupy it not as water occupies a tank, but in the sense that they patrol it, like a guard. They prevent the electron patrol of other atoms from entering, and this patrolled sphere we therefore call the size of an atom, since two atoms brought together by ordinary collisions will bounce off from one another as soon as these loosely occupied spaces touch. When, however, a very energetic particle, like an alpha particle or a swift electron, encounters an atom it can break right through this electron patrol which we ordinarily call the atom, experiencing only small deflections where it passes very near to one of the electrons. In the ordinary case, the nucleus being so small, the particle will pass right through the atom without much ado, but should it, as happens now and then, pass near the massive and forceful nucleus, it will swerve aside like a raider approaching a powerful fortress. The atom is, then, mostly empty space, and what is not empty space is centres of electric, and probably magnetic, force—a very strong centre of force at the middle, and weaker centres of oppositely directed force moving in the outer parts.

If one of the thin gold leaves of Rutherford's experiment were magnified until it was a mile thick, the atoms would be about a yard across, practically touching one another, but the nucleus at the centre of each atom would be about the size of a small grain of dust, a thousandth of an inch or so across. An alpha particle, much the same size, on its way through this layer so sparsely populated with nuclei, would have to pass within four-thousandths of an inch of a nucleus to be turned aside through forty-five degrees, so it can be easily understood that only an occasional particle is deviated through a large angle. It is, however, the existence of these occasional particles that provided the clue to the atomic mystery.

The number and general arrangement of the electrons in the outer parts of the atom in its normal state depend upon the size of the positive charge in the nucleus. Chemical action between atoms must be an affair of the electrical forces in the outer parts of the atom, which forces are not the same all round in all directions, but are patchy and peculiar to the kind of atom, on account of the arrangement of the electron orbits, which have certain known directions. We may therefore say that the size of the charge on the nucleus fixes the chemical properties of the kind of atom in question.

We have frequently had occasion to speak of the mass of atoms. Until recently this could only be found by chemical means. In certain compounds two different elements combine in the proportions of one atom of one to one atom of the other, so that by weighing in a delicate balance the amounts that actually combine, we can find the relationship of the weight of one kind of atom to the weight of the other kind. Knowing the weight of an atom of one element, say hydrogen, which can be estimated by special methods, glanced at when we were discussing Brownian motion in Chapter II., the weights of all other atoms can be found by studying suitable chemical compounds, and these weights are the so-called atomic weights tabulated in all books on chemistry. One atom is taken as standard, namely, for special reasons, oxygen, whose weight is called 16, and the weights of the others are given in comparison.

It must be noted, however, that the quantities which we actually weigh consist of millions of millions of millions of millions of atoms, so that what we are really finding is an *average* atomic weight. Of course, if all atoms with the same chemical properties should weigh the same, as was tacitly supposed until recently, the average gives us the same results as an individual weighing. If we have two bags, one containing a million pence and the other a million shillings, weighing the bags will give us the relative weight of a penny and a shilling, supposing all shillings and all pennies to weigh the same. If, however, shillings minted in different years should be different in weight, although they all have the same purchasing power (which corresponds to chemical property in our atoms), then all we have found is the *average* weight of a shilling in terms of that of a penny.

Now, one of the most important series of researches performed since the war is that by which Dr. F. W. Aston has found it possible to determine the masses of individual atoms. In discussing the electron we have already pointed out that a stream of charged particles in a vacuum tube is equivalent to a current, and is deviated from its course by a magnetic force or an electric force. The force on one of the particles depends upon the charge on it: the deviation which the force produces depends on the mass and upon the speed with which the particle is moving, just as if a ball is hit across a wind the amount which it is blown aside will depend upon the mass of the ball and upon its speed (supposing, so as to get the force produced by the wind the same, that the balls are the same size in all cases). A golf ball is clearly less affected than a ping-pong ball, and a fast golf ball less than a slow one. It is easy to produce a flight of charged atoms in an evacuated tube, either by introducing the kind of atoms required as the trace of gas which remains in the tube, or by putting them as a solid compound on the positive electrode. Using a special arrangement of electric and magnetic forces, which correspond to two different kinds of wind blowing upon our ball, and knowing the charge upon the flying atom, which can be deduced from other considerations, the mass of the atom can be calculated from the amount which it is swept aside from its original path. This amount can be observed, because, luckily, the flying atoms leave their mark upon a photographic plate, set up as a target. If there are atoms of two different masses present their paths will be separated out, like the path of the golf ball and the ping-pong ball in the wind.

Aston's apparatus is, in a sense, a kind of electromagnetic scales for separating out atoms according to their weights, and dropping them into the appropriate places. By its aid he has established an astonishing fact that was suspected, but of which the generality was not realized, just before the war—namely, that the majority of chemical elements do not consist of identical atoms, but of a mixture of atoms which, while having the same chemical properties, have different masses. Thus chlorine, with its atomic weight 35.46, contains atoms of weight 35 and others of weight 37, the proportions being such as to give the fractional atomic weight 35.46. Other elements contain atoms of many more than two different weights: for instance, mercury, of atomic weight 200.6, is a mixture of atoms of weight

202, 200, 199, 198, 201, and 204, the kind of which the greatest numbers are present being given first in this list. This discovery can be summarized by saying that most chemical elements are mixtures of isotopes,[1] isotopes being the name given to atoms having the same chemical properties, but different atomic weights.

The discovery of isotopes brings a great simplification into the study of atomic structure, for, as is illustrated by the examples given, when the isotopes themselves are considered, it turns out that all atomic weights are very close to whole numbers; the fractions which appear when the ordinary chemical elements are investigated occur mainly because these elements are mixtures. It therefore looks as if the heavy part of all atoms of different kinds might be built up of simple particles of one kind —namely, the nucleus of the hydrogen atom.[2] We arrive, therefore, at the conclusion that the nucleus of a hydrogen atom, which is a particle with a positive charge of the same magnitude as the negative charge on the electron, is of special importance for atomic structure. It has received the special name of *proton.* The helium atom weighs four times as much as the hydrogen atom, and its nucleus contains four protons: the nucleus of one type of chlorine atom contains 35,

---

[1] Isotopes is derived from Greek words meaning 'the same place,' namely, in the periodic table, a place in which corresponds to definite chemical properties.

[2] The nucleus of the hydrogen atom actually weighs slightly more than the unit which appears in the heavier nuclei, but there is a reason for this, somewhat too complicated to be considered here.

of the other type 37 protons, and so on. It is to be specially noted that positive electricity never occurs alone, as negative electricity does, but even in its simplest form is associated with matter.

We now go a step further. If the nucleus consisted of nothing but protons an atom weighing 35 times as much as a hydrogen atom would have a charge of 35 units, and would hold round it 35 electrons in the body of the atom itself. It is found, however, that in general the nuclear charge of positive electricity is far less than the atomic weight of the atom in question. For instance, both chlorine atoms, of weight 35 and 37 respectively, have a nuclear charge of 17. This is easily explained if the nucleus contains, intimately associated with its protons, electrons of its own, quite distinct from those extra-nuclear electrons, as we may call them, which circulate round it as the planets do round the sun. The electron has a mass only about a two thousandth of that of a proton, so that their presence does not appreciably affect the weight of the nucleus. We now see the explanation of the existence of isotopes. The positive charge on the nucleus fixes, as we have seen, the chemical proportion of the atom, so all the isotopes of one element must have the same nuclear charge, but different masses. If to a nucleus we add one proton and one electron we do not alter the nuclear charge, since the positive and negative charge added annul one another, but we do add one unit to the mass. We can therefore, on paper, associate any nuclear mass with any nuclear charge—that is, with any chemical properties—we like. Nature does not provide all the different types of atom we thus imagine, but she does provide a large number of instances of this kind. Thus the nuclei of the two different kinds of chlorine contain, one, 35 protons and 18 electrons, and the other, 37 protons and 20 electrons, the net positive charge or *atomic number*, as it is called, being, as we have said, 17 units in either case. The arrangement of the extra-nuclear electrons, governed by a central positive charge of 17 units, gives the chemical properties which characterize chlorine.

The existence of protons as a definite part of the nuclear structure is not a mere supposition. By bombarding light elements with a hail of alpha particles, Sir Ernest Rutherford has succeeded in establishing that protons can be knocked out of them, chipped off them, as it were. In this way a nucleus of another kind of chemical atom is manufactured, an actual transmutation of the elements is effected. The method used by Rutherford detects the rupture of single atoms, and only a few atoms are transformed in each experiment. The experiment never produces a weighable or collectable quantity of any new atom, but it establishes the possibility of the transmutation. Atoms, it now appears, are not unbreakable, they are not discrete entities without physical parts, but are structures with which we can tamper, and with the construction of which Nature has no doubt been playing in the past, and is still playing in the stars. It is this breaking of atomic nuclei that is meant when there is talk of 'breaking the atom.' Strictly speaking, to break an atom, in the sense of breaking off some of the outside electrons, is the easiest thing in the world. It is going on in every flame and in every electric lamp, as we shall see, but when this happens the atom repairs itself by taking up other electrons. No permanent change is made. It is the innermost nucleus, which dictates the structure of the rest of the atom, that is so hard to injure. As long as it preserves its protons the mass of the atom is unchanged, as long as it preserves its charge the chemical identity of the atom is unchanged.

In the case of the heaviest atoms the nucleus is a very complicated structure, containing very many protons and electrons—for instance, 226 protons and 138 electrons in the case of radium. So complex a structure appears not to be stable: it is liable to slip and lose one or more of its parts, which is then thrown right out of the atom with great energy, leaving a new kind of atom. This is the process known as radio-activity, or radio-active decay. Some radio-active elements shoot out a high-speed electron from the nucleus, generally called a beta particle, when it proceeds from such an element: others, as we have recorded, shoot out an alpha particle, which is the nucleus of an atom of helium, consisting itself of four protons and two electrons closely combined. This is a further proof that nuclei (some nuclei, at any rate) contain these components. Some radio-active elements also give out from their nuclei a kind of very penetrating X-rays, called gamma rays. All these radiations are witness to an intense activity, and a very high store of energy in the nuclei in question, and they give convincing proofs that atoms can be transformed into different kinds of atoms, for when a radio-active element has lost an alpha or a beta particle it becomes a new kind of chemical element, with quite different chemical properties from those of its former self. We have, however, to wait for the atoms to break down of their own accord. Nothing we can bring to bear in the laboratory can stop an element that is radio-active from performing; nothing can make an ordinary element radio-active. We witness the phenomenon; we cannot cause it.

All the radio-active elements are very heavy. They fall into three families, each beginning with an element whose atoms give out alpha particles, and become atoms of a different element. These atoms in their turn are radio-active, and suffer change into other elements. The process stops when the chain of transformations reaches one of the ordinary chemical elements, ordinary in the sense that it is stable, and always stays in the same condition. Some radio-active elements decay very fast; for instance, one half of the atoms of the element known as Actinium A undergo transformation in a few thousandths of a second, whereas the atoms of uranium require some thousands of millions of years for half of them to be transformed. What leads to these enormous differences in rates of decay is one of the problems which confront the men working on radio-activity.

To resume, the nucleus, then, is the ruler of the atom, dictating its chemical and physical properties. It is protected by its patrolling electrons, and is so tightly knit together that only the most intense force, such as that offered by the bombardment of alpha particles, can disturb it, and even these particles are unable to get near enough to the more heavily charged nuclei of heavier atoms to do any damage. We have seen, however, that the very heavy nuclei fall to pieces of their own accord, giving out enormous energy as they do so. An ounce of radium, in the course of its decay to its final form, which is the metal lead, gives out enough energy to run a 100 horse-power engine for fifty-four days. This decay, however, takes place so slowly that it is only half over in 1,730 years, but even so one ounce of radium gives out enough heat in an hour to raise one and a half times its own weight of water from room temperature to boiling-point. Such heavy nuclei, then, are the seat of enormous energy, which *they give out when they break up*. The light nuclei, on the other hand, require enormous energy to be put in to break them up, which means that a correspondingly great quantity of energy would be released *if we could build them up.* It can be shown, for instance, that if we knew how to make four hydrogen nuclei—protons—and two electrons combine to form a helium nucleus we should have at our disposal, by manufacturing an ounce of helium in this way, a supply of energy sufficient to run a 100 horse-power engine day and night for eight years. If, then, we ever learn to transmute the elements in any quantity, the energy thus made available rather than the metals manufactured is likely to be the valuable thing. If it *is* made available, that is: it might appear in a form which we could not control, either, say, as a reaction of more than explosive violence or as a very penetrating radiation which we could not confine, a radiation of the type of the cosmic rays to which we have already referred. It is, in fact, quite likely that the cosmic rays have their origin in the combination of lighter atoms to form heavier ones in outer space; exactly which atoms are in question is still a matter for speculation. It seems that only by the manufacture of atoms can sufficient energy be liberated in a single process to give rise to rays of such high frequency as is indicated by the extremely penetrating nature of the cosmic rays.

Let us now leave the ruler, the nucleus, and look at his subjects, the electrons, describing their courses round him in a periodic fashion. Such a periodic motion is the kind of process to which the quantum theory can be applied. We should expect, from what has been said in Chapter VI., that the motions of the electrons would be restricted in a peculiar way, so that the speed of the electrons round their orbits would not be able to have any value whatsoever, but only certain definite values in accordance with the mathematical rules laid down by the quantum laws. The electrons are not like so many free agents in motor-cars, cruising about on a beach at any speeds of which the vehicles happen to be capable, but are rather like trains whose movements take place on fixed tracks and are controlled by time-tables. To an observer who knew nothing of these things the movement of the trains would appear very arbitrary, considering that there is nothing in the mechanism of the engine of a train to prevent it running anywhere and at any speed it likes. In the same way, before the quantum rules were discovered, it seemed natural to suppose that electrons in an atom could move at any speed which their mechanism, as it were, allowed. When electrons form part of an atom, however, the quantum theory provides the time-table and the tracks of the atomic system, or, rather, not one time-table, but a large number of alternative time-tables. The electron system must obey one of these; electrons cannot move at any intermediate speeds round the nucleus, although the ordinary laws of mechanics would permit these speeds. In other words, only certain orbits or tracks, and only certain speeds in these tracks, are allowed.

To say that the electrons have certain definite time-tables comes to the same thing as saying that the atom can possess, in virtue of the movements of its electrons, certain energies, but not energies intermediate between them. When the electrons are obeying one of the allowed time-tables the atom is said to be in a stationary state: the electrons are not stationary, but the value of the atomic energy is. If, now, something happens that causes one of the other possible time-tables to be adopted, then the electrons will suddenly pass to a different series of motions, and the energy of the atom will suddenly change. Suppose, for definiteness, that the energy of the atom diminishes: what happens to the surplus energy? It appears as radiation which leaves the atom. What kind of radiation? Well, that depends upon the amount of energy released. This energy is turned into radiation according to the quantum law. A big parcel of energy set free in one atomic process becomes a packet of radiation of high frequency—that is, short wave-length: a small parcel of energy becomes a packet of radiation of low frequency—long wave-length.

We can summarize this theory, due to Professor Niels Bohr, by saying that a given kind of atom can only exist in certain definite states of energy, which it possesses in virtue of the fact that its moving electrons can only travel in certain orbits governed by the restrictions of the quantum law. If we put energy into the atom, it passes from one stationary state to a state of higher energy: if, on the other hand, the atom changes from a given stationary state to one of lower energy, then the balance of energy is radiated as a radiation whose wave-length is determined by the amount of the balance.

How can we put energy into the atom? Well, we can heat a gas, so that the atoms hit one another hard. If we heat it enough, the impacts—or some of them, at least—will be vigorous enough to raise some of the atoms struck to a higher state of internal energy. Another method of putting energy in is to pass a stream of electrons through a gas in a discharge tube: some of the electrons will hit the atoms hard enough to perform this function. Or, again, we can let radiation of a suitable wave-length fall on the atoms, when some of them will take up energy from the radiation and pass to a state of higher energy. In all these cases the atoms will give out radiation; if the circumstances are suitable, it will be visible radiation—light. What does this mean? Why, that after being put into the higher state—wound up, as it were—the atoms slip back into a lower state again, unwind themselves, and give out the energy so released as light. For a given atom the actual energy change, which governs the frequency of the radiation, will depend upon which two of the possible stationary states are involved as the beginning and the end states of the atom. As, however, there is a set of possible energies, with large gaps between, only certain frequencies are possible for a particular kind of atomic system.

spherical shell of space, like one layer of an onion. This is only a rough picture, for some of the orbits are not truly circular, but are long ellipses; but for our general purpose it will serve. The electrons in the outermost shell, or group, are those which have to bear the brunt of the atom's daily life. They are responsible for chemical combinations: the shock of collisions between atoms falls on them. They are farthest from the nucleus, and so are the least firmly held of all the electrons. A comparatively mild disturbance suffices to make one of them leave its orbit, and go to one of the orbits allowed by the quantum theory in the space surrounding the atom. Since it is not necessary to overcome large forces in this process, the energy changes which attend the vicissitudes of these outer electrons are not large, and so the frequencies of the radiations sent out when the atom readjusts itself are not large. It is, in fact, such changes that are responsible for the lines of the visible and ultra-violet spectrum.

If the atom be sufficiently roughly handled—struck, say, by a very swift electron—one of these outer electrons may be clean removed, and we are left with an atom with, on the whole, a positive charge, which we call an ionized atom. A second electron may then be disturbed in such a way that the ionized atom gives out an optical spectrum of its own: from the optical point of view an ionized atom behaves as if it were a new sort of atom, but, of course, it is not. The nuclear charge is unchanged, and the atom soon picks up an electron and repairs itself. No permanent harm is done, and we can scarcely speak of 'breaking the atom' in this case. If the atom is still more violently disturbed, it may lose two or more of the outer electrons: by using a very violent and hot spark, all the outer group of electrons may actually be peeled off, which means as many as seven electrons removed with certain atoms. An atom which has thus been deprived of its coat of electrons is called a 'stripped' atom by Millikan. It seems that, at the very high temperatures which prevail in some stars, conditions are such that atoms lose not only their outer shell, or coat, of electrons, which we can take off in our laboratories, but also all the under layers of electrons, or underclothes, let us say, that surround the nucleus, and we are left with nothing but unprotected nuclei. We know that nuclei, which are endowed with practically all the mass of the atom, take up very little room, so that we should expect for a stellar substance of this kind an enormous mass in a small space —or enormous density, to use the technical word. As Eddington, who has pointed out how this theory accounts for the abnormal weight of some small stars (such as van Maanen's star, which is about the size of the earth but weighs nearly as much as the sun) has said, a ton of this 'nuclear' matter would easily go into your waistcoat pocket! It is matter with most of the empty space squeezed out. But take one of these stripped nuclei out of its environment of intense agitation, and put it somewhere in the cold on earth, and it would collect electrons and build up a complete atom again.

Putting aside this digression on stripped atoms, the emission of light by a flame or by the glowing gas in a discharge tube, such as the mercury vapour light used by photographers, is an affair of the outermost electrons of the atom in question. Suppose, however, that we expose atoms to very swift electrons. An electron may be displaced from one of the inner groups to somewhere right outside the atom, putting the atom in a stationary state of higher energy. Very soon the vacant place so left will be filled by an electron, and the atom will revert to a state of considerably less energy. Since this energy loss is comparatively large, the radiation which corresponds to it is of comparatively high frequency: in fact, it belongs to the class which we call X-rays. The deeper in the atom the group from which we displace an electron in the first place, the greater the frequency (and the penetrating power) of the X-ray. We see now how it is that solid substances give a line spectrum of X-rays, while to get a line spectrum in the visible region we must have a gas. In the X-ray case, as we are not dealing with outer electrons, it does not matter what bangs or what electrical forces act on the outer parts of the atom: the nearness of other atoms in the solid does not appreciably affect the inner electrons. When the outer electrons are in question, as in the optical case, these outside influences make all the difference. Scratch the surface of an atom, and we get light; stir up its inside, and we get X-rays. Stir up the nucleus, and we transform the whole nature of the atom.

The hydrogen atom, of course, offers a particularly simple case, as it has only one electron, and so there is no question of inner and outer groups, or of a spectrum of an ionized atom. The optical spectrum, which extends from the infra-red to the ultra-violet, has a very straightforward structure, which was the first one to be worked out, and there is no X-ray spectrum. The other kinds of very light atoms have also no X-ray spectra: it is, in fact, not until we come to consider atoms with well-formed inner groups that a well-developed X-ray radiation, with penetrating power, is found. Ordinary hydrogen gas consist of molecules, each of which is made up of two hydrogen atoms; while the electric discharge generally breaks up the gas into atoms, which give out the simple spectrum just mentioned, the molecules also form systems which can give out light, if suitably treated. The spectrum of molecules is always very much more complicated than that of atoms, as seems only natural, since in the molecule we have two or more atoms, each an elaborate system, acting on one another, and combining to produce various intricate joint effects. The spectra of the light given out by molecules, as distinct from atoms, consist of multitudes of lines arranged in groups which produce the appearance of shaded bands, whence the term 'band spectra' is applied to them. All that can be said here is that some of these complicated band spectra, given out by molecules consisting of two atoms only, have been disentangled by the aid of the quantum theory.

We have now seen how the quantum theory, applied to the circulating electrons of the atom, explains the fact that atoms, by themselves, give out definite and characteristic wave-lengths, both in the visible and in the X-ray spectra. The X-ray spectra, being generated in the protected parts of the atom, are very much simpler than the optical spectra, which to the inexperienced eye appear to be nothing but a medley of lines. By the aid of the theory, however, it has been possible to disentangle the most unpromising spectra, and pick out, from the apparent muddle, series of lines obeying beautiful simple laws. The quantum theory has found much of its justification in the effective aid which it has brought to the difficult task of finding a meaning in the mixture of complicated groups of wave-lengths thrown out when we provoke a tubeful of atoms. It has provided the grammar by whose aid we read the language of atomic radiations, and find out, from what was before a string of luminous gibberish (which could be recorded, but not interpreted), the character of the atomic spectra.

It should, perhaps, be added that this picture of electrons in orbits offers certain grave mathematical difficulties, and attempts are now being made to work out the properties of atoms by considering them as masses or clots of waves, subject to quantum laws. On the new theory of wave mechanics, as it is called, the electrons themselves have wave properties, and the paradox by which, on the quantum theory as here explained, waves are given certain properties of particles, in that they seem to be sent out in packets, is completed by giving particles certain properties of waves. Both wave properties and particle properties are needed, as we have seen, to account for the behaviour of light and radiation in all its aspects; the suggestion now is that the ultimate grains of matter and of electricity likewise demand the dual conception if we are to push our inquiry successfully into the finer details. When we treat of light we can consider it as proceeding in straight lines, or rays, so long as the structure of the phenomenon examined is coarse compared with the wavelength of light: for instance, the position of shadows and the elementary properties of such instruments as telescopes, can be worked out by ordinary geometry—the methods of so-called 'geometrical optics'—if we are content to neglect minuter features, to the nature of which we referred when speaking of interference and diffraction. When, however, we come to consider light passing by bodies of the same kind of size as the wave-length, or through minute openings, such as slits, the wave properties become all-important, and the methods of geometrical optics, with its straight rays, are powerless. In the same way, as long as we are dealing with the mechanics of ordinary pieces of matter, such as can be handled, or even seen with the microscope, the ordinary methods of particle dynamics, which were universally used until the last year or two, are good enough: when we come to consider the electron, or the proton, the methods of ordinary mechanics apparently break down, and we are forced to invoke the new wave mechanics. The particle has to be considered rather as the centre of a complicated wave disturbance than as a minute speck surrounded by a field of force.

If a gross, and so not entirely accurate, picture of a very subtle conception may be hazarded, it is somewhat as if the dwellers by a harbour bar, after having always neglected the wave system at the mouth of the harbour, and attached reality to the submerged bar of sand, were suddenly to transfer all their attention to the system of waves covering the surface of the harbour and of the outside water, with a peculiar and emphatic behaviour in the region formerly called the hidden bank, and were to say that the harbour bar was this whole complex of waves. The bar so defined would no longer be strictly localized, but would extend over a large region; there would, however, be a marked local peculiarity to correspond to the old bar. In this respect the analogy is good, but it is bad so far as the waves of the theory of wave mechanics must be endowed with special properties, mainly in the way of laws of travelling, which are not possessed by the familiar waves of the sea. It is probably good, again, in so far as the full fact is both sandbar and wave-system, which are different ways of regarding a reality that includes both of them. The wave aspect and the particle aspect of matter are both useful and necessary; we are now confronted by a possible reconciliation.

On the theory of wave mechanics put forward by Prince L. de Broglie and Professor Schrödinger every ultimate particle is associated with, is the manifestation of, can be represented by—dare one be downright and say 'is' ?—a group of waves with a narrow range of wave-lengths. Fundamental for the theory is the distinction between the 'phase velocity' and 'group velocity' of a system of waves, which is a little bit troublesome. Imagine the surface of a pond over which a wave of fixed wave-length is travelling the whole time. The crest of the wave advances with a certain speed, called the 'phase velocity.' Now suppose another wave of slightly different wave-length travelling over the surface of the same pond in the same direction as the first wave, with a slightly different velocity. At a certain place the waves will conspire to produce a more violent disturbance, a centre of energy, as it were, and this centre may advance with a velocity very much smaller than that of the waves themselves.

It is the velocity of this centre which we call the 'group velocity,' and this group velocity corresponds to the motion of the particle. The velocity—the phase velocity—of the supposititious waves of the wave mechanics comes out to be very much higher than that of light, which is not against the theory of relativity, because these waves are not light waves, which we can start and stop—no signal can be sent by them. The group velocity of the ultimate particle considered we can make anything we like. It is this freedom that makes the theory workable. To each particle velocity we can make agree a special wave-length of the corresponding waves. It cannot be hoped that what has just been said will make a very clear impression on the reader: the new theory is at the same time too raw and too abstruse for clear exposition in general terms to be possible. The conceptions used by the pioneers are of a mathematical nature, and it will probably be some time before they have been sufficiently handled for a general physical meaning, which can be discussed in elementary terms, to be evolved.

The wave-like properties of the electron and the proton are not, however, purely mathematical fictions, for they have been experimentally demonstrated. It has been already mentioned that crystals offer a very fine and very regular structure, by means of which the very short waves of X-rays can be analysed. Now in 1927, Drs. Davisson and Germer succeeded in showing that electrons fired at crystal surfaces, and there reflected, produced wave patterns on a photographic plate of just the kind to be anticipated on the theory of wave mechanics. Since then, Professor G. P. Thomson has managed to make sheets of crystalline matter so thin that comparatively slow electrons can pass through them, when once more wave patterns of the predicted nature are produced. Among the substances used by G. P. Thomson are thin films of crystalline gold, the tenuous nature of which will be understood when it is stated that they are so transparent that quite fine details, such as the bricks of a wall, can be distinguished through them. Still more recently, Professor Dempster has announced that he has demonstrated the wave nature of the proton by reflection at a crystal surface. The predictions of the theory are being confirmed in measured detail, and not just in a vague general way.

The whole subject of spectra, especially in its finer details, has been very much advanced by the aid of the conception of the electron as a wave phenomenon. The new theory is but another example of how new laws, of a fundamentally different character from those worked out by the study of the more obvious features of matter and radiation, have perforce to be formulated when we come down to consider the mysterious ways of the ultimates of physics.

The modern study of the atom, which has revealed the nuclear structure and the quantum states, has vastly simplified many of the old problems of physics, but, like every great scientific advance, has raised a crop of new ones. It has enabled us to visualize all matter as built of only two ultimate things—the electron, or atom of negative electricity, and the proton, or unit of nuclear structure. Together with the photon, or atom of radiation, it has given us an insight into the way in which light is sent out and absorbed by glowing gases, or flames in the most general sense of the word, and lent a meaning to the complicated chords of coloured light sounded, as it were, by the different elements when differently provoked into luminosity. Since all our information as to the constitution of the heavenly bodies comes to us as light, in most cases from glowing globes or clouds of gas in outer space (although in some cases, such as the sun, there is a liquid sphere which gives out light of all possible frequencies), it is easy to understand that the new information on the structure of the atom has had profound repercussion on modern astronomy. The title of Professor Eddington's little book, *Stars and Atoms*, or the fact that Sir J. H. Jean's book on *The Universe Around Us* perforce contains a chapter on 'Exploring the Atom,' serves to show how intimate is the connection between the astronomy of the infinitely little, which comprehends the circulation of the unthinkably small electrons round their tiny nucleus, and the astronomy of the infinitely great, which includes stars bigger than the whole solar system and thousands of nebulae as big as our whole galactic universe. In the celestial bodies the atoms are exposed to far greater temperatures than they are on earth—temperatures of 30,000,000 degrees Centigrade in stellar interiors are deduced by some astronomers—but our terrestrial experience enables us to calculate what will happen at such temperatures, and the results help to explain puzzling observations, such as the abnormal density of van Maanen's star, to which we have already referred. The explanation of the origin of X-rays, offered by the structure of the atom, which has helped modern physicists so much, is equally important to modern astronomers.

If we knew all about the laws of atomic structure we should understand the way in which each kind of atom attracts every other kind of atom, the facts of chemical combination would be cleared up, and chemistry would become a branch of physics. The study of atoms has certainly offered an explanation of some of the simpler properties of the elements. We know, for instance, that the inert gases, which do not combine with other elements, have a very symmetrically arranged and complete outermost group of electrons, as revealed by their spectra and other properties, so that, naturally enough, there are no particular stray electric forces in specific directions to act as handles or hooks for other atoms. The study of the spectra of molecules, and of the energy required to tear an electron from an atom, is helping to clear up the behaviour of simple molecules, but so far we have to rely upon the experience won by the test tube and balance, rather than that of the physicist's favourite spectroscope and discharge tube, if we want to know what atoms combine, and in what proportions, to form complicated molecules. When we pass to living matter, which likewise consists of the same atoms, with their nuclei and electron systems, we are still further from the simple cases of atomic combination which we understand in some detail, and are in regions where even the chemist has to consult with the physiologist before he can say what such very complicated molecules as those of our digestive fluids will do. If we knew enough about the behaviour of atoms when banded into the regiments which represent the big organic molecules, we should be able to anticipate and understand the action of X-rays and the rays of radium on the living cells of our body, just as we can at present calculate their effect upon metals and gases, but these cases are at present beyond our power, and we have to rely upon experiment in each particular case—very often upon uncritical experiment. However little may yet be our achievement in complicated cases, we must remember that anything that concerns the material side of life is an atomic question. If, as a widely travelled observer recently reported, in all the physical laboratories of the world atomic problems now engage the attention of the majority of the workers, it is only because any physical experiment, properly interpreted, has a bearing upon the behaviour of that all-comprehending microcosm, the atom.