UNIVERSITY COLLEGE OF SWANSEA

THE SIGNIFICANCE OF THE ELECTRON

ITS IMPACT ON MODERN SOCIETY

Inaugural Lecture of the
Professor of Physics
delivered at the College on
6 November 1947

by

PROFESSOR F. LLEWELLYN JONES
M.A., D.Phil., F.Inst.P.

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On the other side we have entropy which is frankly of a much more subjective nature than most of the ordinary physical qualities. If colour is mind-spinning, so also is entropy a mind-spinning—of the statistician. It has about as much objectivity as a batting average.

EDDINGTON, *Nature of the Physical World*, p. 95.

Quid est tempus? Si nemo a me quaerat, scio; si quaerenti explicare velim, nescio.

AUGUSTINE, *Conf.* xi. 14.

PRINTED IN GREAT BRITAIN

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ACKNOWLEDGEMENT

Thanks are due to the Controller of H.M. Stationery Office for permission to include the photograph and diagram of Plate II, and to Messrs. Keystone Press Agency for permission to include the photograph of Plate I.

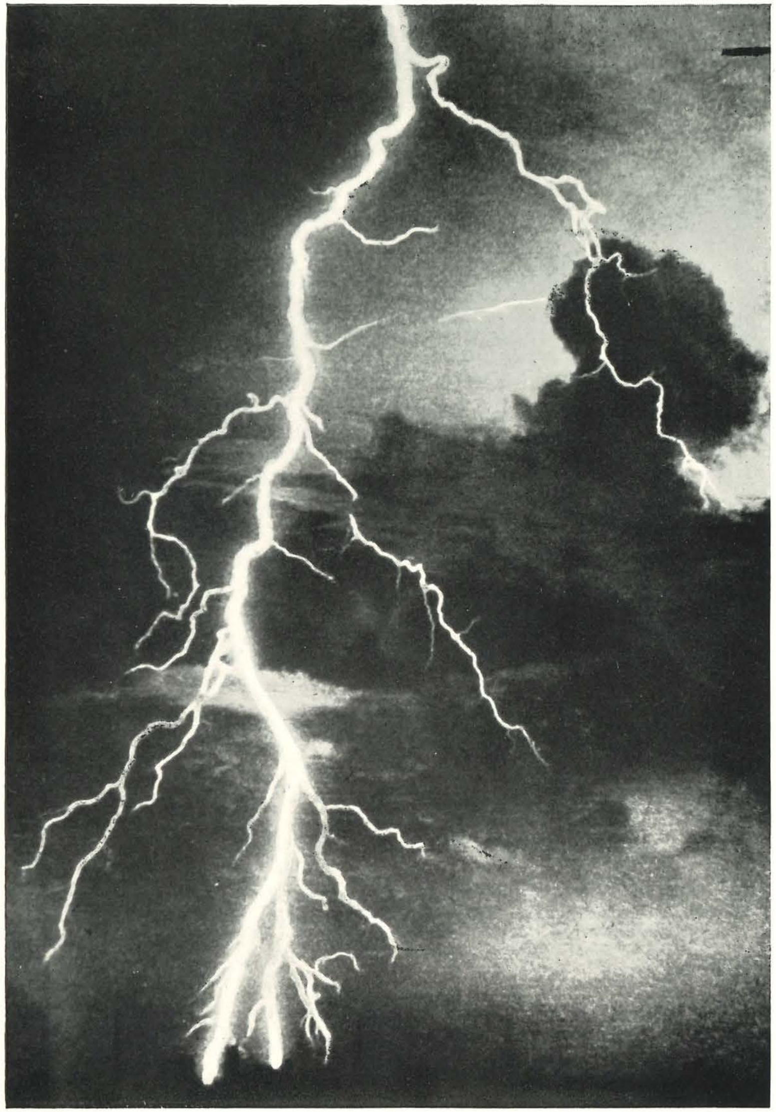

PLATE I. A lightning-flash at sea

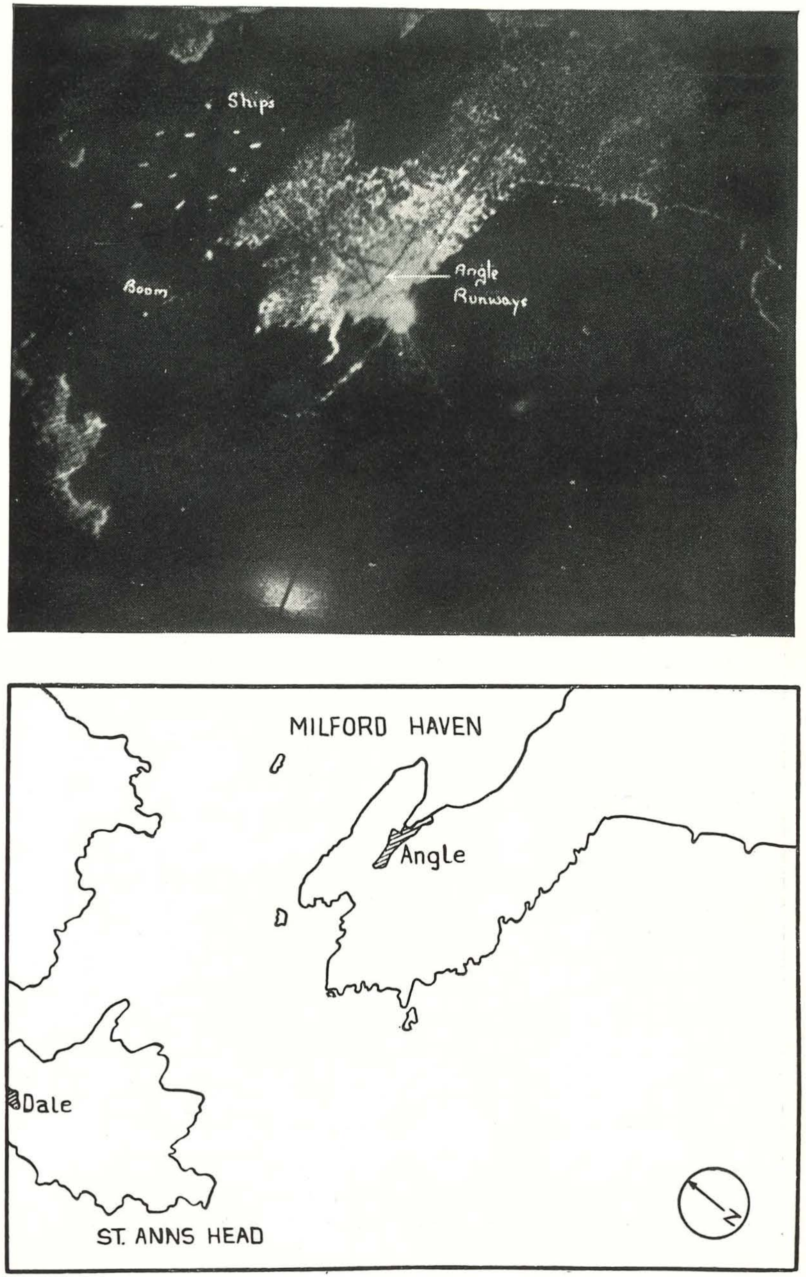

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PLATE II. Radar photograph of Welsh coast near Pembroke, showing ships at sea and runways at Angle aerodrome

I

THE ELECTRON AND SOCIETY

THE year 1947 marks the Jubilee of one of the greatest achievements in the history of science—the discovery of the electron by Sir J. J. Thomson. It is now becoming recognized that the electron is not only transforming the material basis of modern society but that it is also having a profound effect upon modern scientific thought. It is partly for these reasons, and partly also because I first acquired my own interest in electron physics through association in Oxford with the man who had first directly determined the charge on the electron, Sir John Townsend, that I have chosen this subject for my inaugural lecture.

I come here as the second professor of physics in Swansea when the Department of Physics has already been firmly established by my predecessor, the late E. J. Evans. It is no easy task to follow one for whom I, like all his colleagues and students, had such high regard and warm affection.

If we ask the question 'What is an electron?' the short answer is simply—one of Nature's building-blocks, i.e. one of the ultimate structural units of the Universe. Where do they come from, and how do they arise? And, what of the atom? When a quantity of an element, say, a piece of silver, or some of the gas helium, for instance, is continually divided and divided, a limit must be finally reached in the producing of minute bits or particles beyond which those bits or particles would cease to have the properties of that particular element. In one sense this is obvious, otherwise, if one could go on indefinitely subdividing and subdividing one would arrive at nothing at all. A halt must be called somewhere, and the limit is reached with the atom. These atoms are, of course, exceedingly minute. For instance, if a single drop of water were to be magnified until it became as large as the earth, then an atom of one of the elements—hydrogen or oxygen—in the water would appear only to be about the size of a pea.

For many years, atoms were thought to be hard, smooth, elastic, but indestructible little spheres—like minute billiard-balls—and in all chemical changes, such as in burning, for instance, no matter how fiercely, the atoms always remained intact. All they did was to change partners—like dancers in a Paul Jones. It was only at the end of the nineteenth century that it was discovered by J. J. Thomson that in an electric discharge through a gas, atoms could be subdivided further, and when this was done, the name given to the little sub-atomic fragments from the outer part of the atom was the electron. This breaking off of electrons from atoms is called ionization, and one simple way of carrying it out is to shoot fast-moving electrons at the atom, just like minute machine-gun bullets—a process discovered by Townsend.

Thirty years later, when the control of more powerful and heavier projectiles was developed, the innermost parts of the atom could also be broken into. As is now well known, this led to the discovery of many other fundamental particles, some heavy, some light like the electron; some with positive electric charges, some with negative charges, and some with no charges at all. These finally led to the development of the atomic bomb, but, in many respects, the electron is still the most fundamental and most important of them all. Here we are not concerned with the whole family of ultimate particles of matter, but they are grouped in the following table although the existence of some of them is still not yet definitely established.

Fundamental Matter Particles

Mass: *Light*	*Medium*	*Heavy*
Electron Positron Neutrino (?)	Meson	Negative proton (?) Proton Neutron

In spite of the fact that, individually, electrons are exceedingly minute, collectively, in great numbers, they exert an enormous influence in everyday life. When once they break away from the restraints of the parent atom, and wander about on their own, they give rise to the diverse and wonderful phenomena known as 'electrical phenomena'—they are, in fact, all we usually mean when we speak of ELECTRICITY. As such they enter into practically every aspect of our material existence. Dashing in their billions through wires they generate the heat which we utilize in our electric fires and our electric lamps. Travelling through the windings of electric motors they produce the forces which turn the wheels of industry and transport. Careering madly through gases, colliding with and tearing up other atoms, i.e. ionizing them in the violence of their path, they produce the electric spark, which may either be the tiny light in the sparking-plug which actuates our motor-cars, or the peril of the gigantic lightning-flash.

Again, when gathered together to form dense clouds surrounding regular arrays of the positive cores of atoms from which electrons have been torn (and called positive ions) electrons give rise to the properties we have always associated with metals. By forsaking one atom and attaching themselves to a neighbour instead, they set up the ionic forces of attraction which hold together the molecules of physical chemistry. And, in another way, by spinning on their axis, electrons control the linkages which underlie the architecture of molecules in organic chemistry. Further, in its interpretation of the origin of spectral lines, and of the extra-nuclear structure of the atom, the success of the electron has been truly amazing. Success has followed success when the ideas of ionization and atomic structure have been transported from the earth to the stars, and so helped to solve what hitherto had seemed a completely insoluble problem—the problem of the internal constitution of the stars.

But probably the best-known and most-publicized application of controlled electrons is to be found in the thermionic valve or electron tube. Around the application of such valves has grown an entirely new and important industry—that of electronics. Applications in the field of radio and broadcasting television and the talking film are too obvious to mention, but other industrial applications are not so well known—or their impact on our present society not realized fully enough. For instance, the comparatively slow motion of electrons through a gas discharge lamp—sometimes called the fluorescent or daylight lamp—is a very efficient means of producing light—more so than the ordinary electric filament lamp. When it is remembered that in this country our electrical power is generated mainly through the use of coal, it has been stated that if fluorescent lighting replaced filament-lamp lighting in this country the entire output from two large power-stations would be saved in every year. The application of electron tubes to generate very high-frequency electric waves has revolutionized many industrial processes, such as the processing of plastic emulsions, and the tempering of steel for bearing or wearing surfaces can now be done in a few seconds without a furnace. Finally, extremely complicated mathematical equations can be solved in fractions of a second, the result remembered, and later adapted to other complicated equations, in modern electronic computing engines—electronic brains as they have been rather picturesquely termed.

However, one of the most fascinating applications of electron tubes is that associated with the word 'radar'. Most of us are now familiar with the striking successes obtained by the Allies in the last war through the use of radar, but the revolution so produced is nowhere more strikingly brought out than in the field of naval warfare. Compare typical fleet actions in the two wars. Langhorne Gibson and Vice-Admiral Harper, in their study[1] of Jutland, write as follows of the night encounter of 31 May 1916, when the entire fleets of two great empires met, and the stage seemed set for the greatest naval action in the annals of history:

> Jellicoe had determined to avoid a general night mêlée of the fleets at all costs. The normal risks of battle become magnified beyond all bounds . . . in the dark—the collisions, the loss of order, the hopelessness of distinguishing friend from foe . . .

and the result, after the German High Seas Fleet had crashed through the light craft in the rear of the Grand Fleet, Harper goes on to say:

> . . . the fleets were drawing apart, yard by yard, mile by mile. . . . Even as they had met, they were separating in ignorance.

The Battle of Jutland is almost a classic in the fallibility of signals and intelligence in the pre-radar era. How different was the last war. The following is a quotation from an official description[2] of a night naval action controlled entirely by radar:

> The two forces continue to close. New ranges and range rates automatically re-position the mighty guns . . . the master salvo

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[1] *The Riddle of Jutland*, p. 228. Cassell, 1934.

[2] *Radar. A Report on Science at War*, p. 40. H.M.S.O., 1945.

key is closed, and with a mighty roar nine 16-inch shells go hurtling through the night. So sensitive is the radar that the operator can 'watch' the shells move across his screen towards the target 'pip'. Sure enough, as the operator watches, the 'pip' slowly fades from the screen. The ship has been discovered, identified, tracked, fired upon, and sunk without a man seeing it visually.

The mounting of our bombing offensive over Germany was accomplished in its greatest intensity only with the aid of devices such as P.P.I. which scanned the territory below, through darkness, fog, or cloud, by means of very short radio pulses generated by special electron-tube oscillators—magnetrons. In this way the operator could 'see' the ground over which he was flying on the scanning-screen of his oscilloscope during dense fog or at night when ordinary visibility was nil. Moreover, the use of such devices is not limited to war: they have similar uses in peace. For instance, they can just as easily be fitted to our fast liners to render sea navigation as safe in dense fog or at night as it is in bright sunlight, and thus render impossible again a disaster at sea like that of the *Titanic*.

Now the cataloguing of the new technological developments brought about by the controlled electron does not complete the contribution of the electron to society. In fact, the invention of the wonderful electronic devices which we now know did so much to win the war was, in itself, far from sufficient without the discovery of an entirely new and very important technique of applying our resources to the best advantage. The science of war does not consist only in devising better and more efficient weapons—important though they are, but it also consists in applying our maximum effort where that is most required. This new technique which was created during the last war is called 'Operational Research'. It is a sort of statistical assessment of all operational data, scientifically obtained, and it was in this new field of applied electronics that the need of it was first felt, and in which it was first developed. This may yet prove to be one of the most far-reaching indirect consequences of the general application of science in war. The new technique, which grew out of the hard necessities of the military crisis of war, has lessons for us which may well be applicable to society in other crises, economic as well as military. The enormous importance, success, and widespread application to diverse fields of this new technique was one of the great discoveries of the war. Further, this University can take some pride in the fact that it was one of its earliest members—one of the first research students of the Physics Department—I refer to the late Professor E. J. Williams, F.R.S.—who did so much to develop this new technique especially in the naval war. The technique proved to be both highly successful and of far-reaching application even to very large-scale operations. Now certain aspects of an economic crisis are similar to those of a military crisis in that certain commodities, and classes of man-power, and so on, are in short supply, so that it is necessary to use our resources to the best advantage. And as it was in just this sort of problem that the methods of operational research proved so useful during the war, there is reason to believe that the application of similar methods might still be of service to us to-day, when maximum efficiency is required with restricted means.

II

THE PARTICLE ELECTRON

So far I have mainly dealt with the technological applications of the electron and its direct impact on modern society. There is, however, another and very important aspect of the electron, and that is the significance of the *concept* of the electron itself. Great though its interpretative triumphs are there is one question which we have not yet answered completely: 'What is the electron?' What we have been dealing with so far is hardly in the realm of pure scientific research. The great applications of electronics were due rather to large-scale and planned development than to unplanned pure research of the kind from which nearly all the great discoveries of science with fundamental significance have sprung—most of them in our universities. Let us, therefore, now survey the fundamental researches which have been carried out in an attempt to answer the question 'What is the electron?' This story is really more fascinating and enthralling than any detective story, and it has the advantage that the mystery to be solved actually gets deeper the more the solution progresses.

Now the question 'What is the electron?' has long been preceded by two other questions: 'What is matter?' and 'What is Electricity?' and the centuries before the discovery of the electron were characterized by the complete failure of all attempts to answer those questions. The electron certainly is composed of matter and electricity, so the two older questions here occur together in dealing with the electron, and this fact has influenced our concept of the electron. The repeated failure to obtain satisfactory answers to the ancient questions: 'What is matter?' and 'What is electricity?' has finally forced another line of attack—a method long used in science—and that is to regard the two apparently different questions as aspects of one *fundamental question*. Such a process has philosophical advantages. It was J. J. Thomson himself who laid the basis of this line of attack. He showed that if electricity were a basic entity, as it were, then, when compressed to such a minute size as the electron was believed to be,

then that entity would exhibit inertia, which is just the fundamental property which characterizes pure matter. Thus for an electron, electricity and matter are one and the same thing—the electron would not only be the fundamental unit of electricity but it would also be the smallest fundamental unit of matter. Such an elegant and simple picture, however, unhappily has its difficulties. If that were the whole story, then what of those other particles which we saw in the table above: proton, neutron, meson, &c., which we know form an integral part of the structure of matter? The situation is extremely difficult, and its full solution has still to come, but we do have a pointer in the theory of relativity. It is clear that we cannot build physics on the basis of matter alone, but relativity tells us that energy represents matter, so that matter can be regarded as simply a high concentration of energy, so that all physical events may eventually be explained against a new background of structure laws for energy or the field.

Let us return to the apparently simple electron and trace the brilliant sequence of researches which brought us to the limit of the idea of the particle electron.

As mentioned earlier, the first simple property of the electron, i.e. the magnitude of its charge, was first estimated in an outstanding experiment by Townsend fifty years ago. Since then we have the amazing work of Millikan who showed that small electric charges were actually composed of a discrete number of electrons, thus establishing beyond doubt the atomic nature of electricity. Previously, J. J. Thomson had measured the ratio of the electron charge to the electron mass, by bending a stream of electrons in a discharge tube, so from both results we now have the mass of the electron as well. The theory of the equivalence of mass and electricity in the electron then enabled the actual radius of the electron to be calculated—provided always the electron really was a small spherical, or nearly spherical, body. The next step was to attempt to make electrons visible, but a moment's consideration showed that to make the smallest entity in the universe visible was completely impossible, as one cannot pick up a pin-head when wearing heavy fur gloves—or again we can only see small cells under a microscope because we have something much smaller—the waves of light—to aid us to see them. But we have nothing smaller than the electron—therein lies its uniqueness.

But at least if one cannot actually see the electron—because there are no waves small enough, we can at least try to make their paths visible to us in virtue of the damage created among other atoms. We can in fact do this owing to a most ingenious device invented by C. T. R. Wilson. Wilson knew that moisture, or dampness, in a clean gas tends to condense into small drops more easily if the gas atoms are charged by having an electron too many or too few. Moisture always tries to find nuclei to condense upon and in the absence of anything else, dust, for instance, charged atoms, i.e. ions, serve the purpose. When fine dust is present in damp air we get the condensation of the moisture on the dust to form a mist. When there is a lot of dust, and a lot of dampness, we get the typical London fog. Seeing how common these are in this country, it is no wonder than an Englishman saw how to adapt this principle to scientific ends.

What Wilson did was to obtain first a perfectly clean, but damp, atmosphere. Since there was no dust, there was no condensation, and no mist. He then allowed fast electrons to pass through the damp gas and ionize the atoms in its path. Nuclei were thus formed for the moisture to condense upon—so we get a thin track of mist. By shining a light on it the mist track shows up as a bright line. Many people, who have never seen a cloud chamber, are yet familiar with this effect—especially those who lived in southern England during the war. What else are the well-known vapour trails of high-flying aircraft than condensation tracks produced by the deposition of moisture on to the ions in the exhaust gases from the engines?

Of course, any fast atomic or sub-atomic particle will produce tracks in this way—not only electrons. For instance, we have proton tracks and α–particle tracks, which are usually firm thick lines, very nearly straight, whereas electron tracks can readily be curved by the effect of a magnetic field. In fact, each type of fundamental particle has its own type of track, and the examination of photographs of Wilson tracks produced by the particles emitted in various atomic processes has resulted in the discovery of entirely new ultimate particles. Some particles discovered in this way, the meson, for instance, may possibly have been generated by some primordial process occurring in the depths of space. Consider for one moment the spiral nebula known as Messier 101 in Ursa Major. There is reason to believe that this agglomeration of primordial matter represents the birth of other whole universes. The events there, which we record to-day, have taken place at distances of millions of millions of millions of miles from us, but what is more interesting, millions of years ago. Actually, the light from this nebula takes one and one-third million years to get to a photographic plate on this earth. Accompanying the birth pangs of new universes new processes, such as the annihilation of matter and its condensation from radiation, are taking place, processes which no one dreamed might be repeated on this earth. But here the Wilson cloud chamber has stepped in and shown us these new fundamental processes occurring right here on earth.

Photographs have been obtained of tracks which are unlike those made by any previously known particle, whether light like the electrons or heavy like protons or neutrons. These new tracks are now believed to have been made by a new ultimate particle which although lighter than a proton is about 200 times heavier than an electron, so it is called the Meson. In a similar way was discovered the positive electron or positron.

III

PARTICLES AND WAVES

LOOKING back, then, it will be seen how apparently complete was the picture of the electron, slowly built up over more than a third of a century—we knew its charge, its mass, its radius, and the track it made through matter—that picture, so simple, so complete, so self-consistent, had only one thing wrong with it—it could not be true, because it could not fulfil all the known facts.

It comes about in this way. We are all here familiar with what may be termed two sorts of activity or, more specifically, two methods of transporting energy. In the first place we have the idea of projectiles—so common in warfare, for instance. When we want to transfer a great deal of energy to a certain piece of matter, say, a battleship, we project at it bodies moving at high speed—shells. Billiards is a more harmless game built up on this principle—the idea of particles moving about and colliding with other particles, and so on, and the mechanics and properties of this game are well known. Similarly every gunner knows how accurately he can predict the path of his shell from an elementary knowledge of mechanics—and such a problem is common in matriculation papers.

On the other hand, there is another sort of activity, completely different from that of particle motion, and that is wave-motion. We all know how energy and power can be transferred by waves. Only recently, here in Swansea we experienced a dreadful storm at sea in which great and fatal damage was done to shipping. How was the energy of the Atlantic rollers and waves transferred to ships here in the channel, other than by wave motion? The properties of waves are well known and documented, and nothing could be more different from particle motion. Particles go straight or in gently curved paths—at any rate in localized tracks, but, on the contrary, waves must spread out. In fact, that is one of their distinguishing properties. The difference between a particle motion and a wave motion is well illustrated by comparing what happens when obstacles are placed in the path of the motion. As in billiards, an obstacle in the path of a particle results in a *collision*, in which the particle is diverted to another direction, but still along a localized and definite track—otherwise billiards would be impossible. But what happens when an obstacle is placed in the path of the wave? Here the answer depends on the circumstances—if the object is much bigger than the wave then advancing to the obstacle the wave is sent back—spreading backwards. That is the principle of the breakwater—*but* the wall must be *big* to be any good. But what happens if the obstacle is not very large compared to the wave? Well, everyone knows that the wave sweeps over it, and is only disturbed slightly. For instance, Atlantic rollers sweep round small headlands or partly submerged rocks, radio waves bend round hills—otherwise broadcasting would not be possible—sound waves bend round ordinary objects—(because they are small compared with sound waves)—and so on. This is a *fundamental property of waves*—one might almost say that it is what we *mean* when we talk of *waves*. So much so that if we have *waves*, then we must find, under the appropriate conditions this *bending*, or *diffraction* as it is scientifically called. Conversely, and this is extremely important, if we come across the phenomena of *diffraction*, then, by all we believe in physics, we must be dealing with *waves*, *and only waves*.

Although they eluded investigation for very many years, it was finally established, *by just this very criterion*, that X-rays were a wave motion. Consequently, if we direct a beam of X-rays at minute objects we should get a *diffraction pattern*, as it is called, just as we get with, for instance, the light from a lamp in a fog. The only trouble is that X-rays are so small that no one for years could find any obstacle small enough to show up this effect, until the brilliant idea was suggested by v. Laue to use groups of molecules in a solid such as a crystal. Thus, when X-rays are directed upon a thin foil of metal and then caught on a photographic plate a succession of concentric circles, or diffraction rings as they are called, are produced on the plate.

Now, it often happens that an essential and far-reaching advance in science is achieved by considering an analogy between apparently unrelated phenomena. In this process, ideas created and carefully developed in one branch are successfully transferred to another. G. P. Thomson, son of J. J. Thomson, shot electrons at a thin foil in the same way as was formerly done with X-rays. The result obtained on the photographic plate was a succession of concentric rings, and an astounding similarity with the case of X-rays was established, and it must be agreed that if those two similar patterns in the plates are to mean anything, then they must mean that electrons behave like waves. Thus, by the very same generally accepted arguments by which we conclude that, for

instance, light consists of waves, radio consists of waves, sound consists of waves, we have now to say that electrons behave as waves. This would not be at all astounding or inconvenient, had we not seen previously how an accurate picture had been carefully built up over a third of a century, not only showing the electrons as a particle, but actually finding all its dimensions and properties. The situation appears impossible.

But worse is to follow. If we talk of waves, we must be able to answer the question: 'Waves in what?' Light and radio waves are in the ether; sea waves are in the sea; sound waves are in air, and so on. But, in what are electron waves? Now here lies the difficulty. These electron waves have no physical reality or existence at all. They are simply *mathematical expressions* representing oscillation in an *n*-dimensional abstract medium. In mathematical language they are just symbols in an abstract hyper-space, which has nothing *whatever* to do with the 3-dimensional Euclidian space of our ordinary everyday experience. The consequent inference from this is very important. The electron is not only the fundamental unit of electricity but, in some views, it may also be the fundamental, smallest unit of matter. And the electron has vanished into 'thin air'—it has been dissolved into waves—which only occur as a mathematical abstraction. And, of course, with the electron goes both matter and electricity—in fact all. Or so it seems. Some scientists, notably Sir James Jeans, took this view. He was forced to the ideas inherent in the Idealism of Berkeley, and, in order to give these abstractions sufficient 'reality', as it were, he was led to postulate God, in whose mind these so-called abstractions would have 'existence'. Further, since these abstractions were of a mathematical type the God postulated must be a mathematician. Science, however, was not content to let the matter rest like that—it could not give up all the real properties of the particle electron. In trying to resolve the paradox into which the concept of the electron has driven us, we have first to consider how science makes advances at all. Science is not just a collection of laws, nor only a long catalogue of facts. In the words of Einstein and Infeld,[1] 'It is a creation of the human mind with its freely invented ideas and concept. Physical theories try to form a picture of reality and to establish its connection with the wide world of sense impressions.'

In the past, many theories have been propounded, argued, then rejected owing to some disagreement with some experimental fact. No matter how perfectly a theory fits the facts known at the time, it nearly always happens that some time later a new discovery is made which requires a new theory or a new discussion of fundamentals. The test of any theory is not its elegance, nor its conventionality, nor its grotesqueness, nor its agreement with other accepted propositions or dogma—the test is simply what will it do? Relativity, compared with Newton's theory, is really utterly fantastic yet is to-day accepted in preference to Newton, just because it fits all the known facts rather better. Thus, complete freedom of thought is the very life blood of the scientist. This ready discarding of long-accepted ideas as soon as they are superseded by new discoveries is very characteristic of science, and this fact is responsible for its rapid growth. The crux of this attitude is the experimental basis of the subject, and the constant training of one's eye on the correspondence between the results to be expected from the best theory and those actually found in nature.

Considerable credit and admiration have sometimes been lavished on the philosophers of the Great Age of Greece, for their propounding of theories which may

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[1] *The Evolution of Physics*, p. 310.

appear to bear a superficial resemblance to the latest creations of science. For instance, that matter must consist of atoms was upheld by Democritus and Epicurus, while the opposing theory of continuity was upheld by philosophers of 400 B.C. On the other hand, what other alternative views were possible? There aren't any! Further, not the slightest evidence was brought forward to support either view, the rival views were just propounded and discussed. We must, perhaps, be careful not to over-estimate the ancients in this respect. Aristotle postulated that heavy bodies fall with speeds proportional to their weights, but apart from one almost forgotten criticism there is no record of any serious attempt to check this by experiment, with the techniques they certainly possessed, for about 2,000 years. Galileo, who probably was the first physicist, tested and disproved the theory on the leaning tower of Pisa, simply by dropping two different weights and watching them reach the ground together.

The modern physicist, when faced by an apparently impossible dilemma about the nature of the electron, is not satisfied with discussion of the problem in a search for logical or other loopholes. He presses forward, not allowing himself to be overcome by the new ideas, but simply whenever possible he adapts those very ideas as he goes. What has happened in this case? If an electron acts like a wave, then let us see what kind of wave it is, and how we can use it. From this comes one of the most fascinating and powerful applications of the electron that has yet been made. I refer to the electron microscope.

The original suggestion of de Broglie, later confirmed by experimental work of the type carried out by G. P. Thomson, made the wavelength of the matter-wave inversely proportional to the mechanical momentum of the material particle. Thus the wavelength λ is determined by the formula

$$\lambda = h/mv,$$

where m is the mass of the particle, v its velocity, and h is a universal constant named after Planck, the discoverer of the Quantum Theory.

Thus the first thing we find in considering electron waves is that the all-important wavelength depends on the speed of the electrons; and the faster the electron moves, the shorter becomes the wavelength. Now it is easy to make electrons move fast or slowly, as desired—we do it in any ordinary wireless valve—so that, in other words, we can get electron waves of almost any desired wavelength. This fact is the germ of a wonderful idea, which was at once adapted in those instruments used for viewing the very small. Now, we all know that when we wish to observe exceedingly small objects, like the cells of living tissue, for instance, we employ an optical microscope. However, if we try to use such an instrument to look at very much smaller bodies, like the viruses that were believed to exist even though they could not be seen, then the optical microscope fails. The reason is not far to seek. In a microscope we see objects in virtue of the obstruction they offer to rays—or I should say waves—of light. We have seen previously that objects only obstruct a wave if that object is not small compared with the wave—it must be bigger than the wavelength, to be able to cast a coherent, distinguishable shadow. The smallest living things, the structures of large molecules, let alone molecules themselves, are far smaller than the wavelength of the light used in the best and most elaborate optical microscopes—even the ultra-microscope. The only way to see these excessively minute particles is to use waves which are shorter still—so short that they

are small compared with even the smallest object to be viewed. This rules out light waves—but not electron waves, as we have seen that we can make these as small as we please, simply by speeding up the electrons. For instance, an electron accelerated by a potential difference of 30,000 volts has a wavelength which is about 25,000 times smaller than that of ultra-violet light. The instrument which uses electrons in this way is called the electron microscope, and such an instrument can render visible, owing to the enormous magnification now possible, objects which are about 100 times smaller than the wavelength of ordinary violet light. The practical limit is nearly one-half of this. When one remembers that this length is only about twenty-five times the diameter of a hydrogen atom—the smallest atom in nature—and that most molecules are very much bigger than this, it is readily seen that the electron microscope takes us right down to the ultimate structure of matter itself—certainly down to the bulky molecules of organic chemistry. Let us see what we find there.

It has for some years been believed, chiefly from work with X-rays, that all macroscopic matter—that is, matter as we know it in everyday life, such as bits of common salt, pieces of clay, diamonds, &c., are really crystalline in structure—indeed in the case of a diamond that is obvious, but it is not so clear in other cases, such as with pieces of metal, for instance. But, to be crystalline means that all the individual atoms, which compose the substance, must be arranged in regular array—not in an amorphous mass—say, like a football crowd leaving the ground, but rather like drilled guardsmen on parade. It is easy to accept this view with such obviously crystalline substances as a diamond, or common salt, but it is not so easy to believe it in the case of a metal—still less is it at all credible that the atoms in such an apparently amorphous agglomeration as the particles of a smoke—or, say, the dust from a flame. Consider the photographer's flashlight—a piece of magnesium is burned, and afterwards it leaves a lazy white smoke. Are we to believe that the individual and freely moving atoms of the oxygen from the atmosphere and the atoms of the burned metal arrange themselves to form regular cubic arrays? Microphotographs taken with an electron microscope show that the smallest particles of the smoke consist of minute cubes composed of regular arrays of atoms of magnesium and oxygen, and this is conclusive proof of the astonishing fact that even small free aggregates of atoms of certain substances actually do band themselves into regular array.

In this chemical field the electron microscope helps to bridge the gap between the aggregates of molecules which make up long chains and the crystalline lattice separation, and many problems of industrial importance are concerned with this range. Colloidal suspensions, smokes, pigments, clays, and insecticides are but few of the materials whose structure has been investigated by the electron—especially in regard to the size and distribution of the elementary clusters of molecules.

In the applied sciences, too, the electron microscope is proving a valuable tool. One of its earliest applications was to solve problems involved in the hardening of steel, and the new technique also yields valuable information about the state of machined surfaces and other aspects of metallurgy such as twinning and precipitation in non-ferrous alloys. However, one of the most fascinating applications of this new technique lies in the field of biology—in the study of the smallest living entities, and it is in this biological field that this new technique of physics is making startling contributions. It has now brought us to the point when photographs can be obtained which represent almost the smallest aggregate of molecules to which we can ascribe the properties of life. The new possibilities thus opened are obvious.

For instance, let us consider the virus. These are exceedingly small particles, or entities, or what not, which are believed to consist partly or wholly of nucleo-proteins. Ever since they were first identified there have been speculations as to whether the virus particles might be regarded as a gigantic molecule—which therefore cannot have smaller constituents with the property of the complete virus; in other words, whether or not it is one of the smallest particles of living matter, or whether it has any structure. The electron microscope has here given a definite answer, as it has shown that a virus still can have an elaborate internal structural differentiation. Bacterial cultures are sometimes attacked by a mysterious epidemic, and d'Herrelle, in 1918, gave the name of bacteriophage to the mysterious cause of this. He further maintained that bacteriophages were probably ultra-microscopic living organisms, parasitic in bacteria, but reproducing themselves in the presence of living matter and destroying it in the process. Direct proof was lacking until as late as 1942, when the electron microscope showed how it was done, and a photograph was obtained of a bacterial cell actually being disintegrated by the pressure created by the tremendous multiplication of the bacteriophage buried and reproducing themselves within it.

IV

THE SIGNIFICANCE OF THE ELECTRON

THE diversion into the successes of the electron microscope must not obscure the fact that we have left our speculations into the actual nature of the electron in an unsatisfactory state. We have seen that an electron has, at the same time, the properties of being a wave-motion and, also, the properties of being a particle. This illogical duality is no better illustrated than in the design of the electron microscope itself. Its great advantage lies in its high distinguishing power for small things, and this, of course, is due to the electron being like a wave. But at the same time, the lenses which accomplish the focusing are designed on the basis of the electron being a particle. In fact, we have our cake and eat it. However satisfactory this may be from a utilitarian point of view, it is highly unsatisfactory from a philosophical standpoint. The fact that an electron has undoubted wave properties is utterly inconsistent with our everyday notion of what a particle of matter is.

This is seen at once when we ask the simple question: 'What speed has that particular electron, just at that particular spot?' The question has a definite answer for an ordinary particle of matter, as any gunner knows. Knowing the initial velocity and position of a shell, he can calculate its speed at any subsequent spot accurately. In that sense the motion of the shell is completely predictable—determined. This has been the basis of the application of science since Newton's day. Thus, after a collision, two billiard-balls travel in definite straight lines, which are completely predictable. Hence, if an electron is just a small particle (like a minute billiard-ball) then its future motion should always be completely predictable according to Newton's laws.

On the contrary, this is just what we cannot do with an electron. When an electron collides with a small obstacle (an atom) it just spreads out on the other side in an indefinite direction, and it might finally turn up at any point where a wave sweeping over the obstacle could be. It does not travel in a definite path like the billiard-ball. Further, since the electron's motion and speed are

determined by a wave, it is not possible to say that the electron is in any localized spot, simply because a pure wave cannot be in any localized spot as it tends to spread out all over the medium. You just cannot calculate where the electron is, although you may know the speed it has. However, if you cannot specify those two conditions together, then you cannot work out even the simplest path of an electron, any more than a gunner could calculate the trajectory of his shell if he did not know the speed of the gun-muzzle. Consequently, the final result to which our concept of the electron has driven us is that we cannot make the simplest calculation to predict the path of a single electron—a calculation which is so easy in billiards. Further, in the sense used earlier, the path of an electron is no longer determined by any cause of which physics has any present knowledge. Strict Determinism has, seemingly, been pushed out of Physics. Certainly a surprising result.

But this result has been formulated by the German physicist, Heisenberg, into his famous 'Principle of Uncertainty', in which it is maintained that the speed and the position of a particle of matter cannot both be exactly specified together. But at this juncture one may well wonder at the everyday applications of science and the great accuracy of its predictions in various applied fields. If there is a fundamental uncertainty, why do we not notice it when dealing with ordinary objects? In other words, if there are no laws to describe the motion of a single electron, how can we calculate accurately the motion of very large numbers in our dealings with large-scale bodies and electric currents?

The answer to that question can be seen by considering the type of problem which faces life insurance companies. As far as they are concerned there is nothing more uncertain than the span of human life, especially under present-day hazards. There is, in fact, absolutely no information in the possession of such a company upon which they could calculate exactly the length of one's life, in order to fix the premiums to their advantage. How do they do it then? They work statistically with probabilities. From previous statistics they know that so many people, in such and such walk of life, die at a certain rate of so many per annum. They then charge such people premiums sufficient to cover the average loss rate. But, in any given case of a single individual, they can calculate nothing at all exactly on the information they possess. All they can do is to work on averages over large numbers of persons. The sound financial positions of such companies amply testify to the accuracy of the calculations.

Let us make an analogy with electrons. We can all agree that the idea of an electron wave simply does not make sense, because no one can say what it is that does the waving. On the other hand, if we try to stick, at all costs, to the idea of an electron as a particle, then we can only do it by giving up all hope of ever describing how it is going to move, because we have no laws whatever to describe even the simplest motion of a single electron. The dilemma seems hopeless, but let us at this point apply the analogy. In actual practice we do not deal with just a single electron. Even in the smallest piece of matter, or in the smallest electric current, of everyday life, there are millions upon millions of them together. Their motion is governed by a wave, but we do know exactly how a wave moves, and spreads, and so on, and we can, quite sensibly, talk of the millions of electrons spreading or moving like a wave. After all, we often speak in such terms in everyday life. We talk of a crowd sweeping like a wave over the barriers of a Rugby field, and as a description of the motion of a large number of people it is

quite good. We could almost press the analogy farther to calculate the motion of the crowd as it converges to the exit—all the streamlines converging as in a river narrowing at a gorge. But still, we do not mean that all members of the crowd have merged into a continuous medium. We know that the crowd is still composed of distinct beings. So with electrons, and we can say that where the wave is strong, at those places there are a great many electrons; and at those places where the electron wave is weak, we shall say that there are a few electrons. This is at least a *modus operandi*. Thus while no one can calculate and predict the future motion of a single electron, we are able, by using statistical methods, like an insurance company, to predict with great accuracy the future motion of a large cloud of electrons. That is why our calculations with large-scale bodies, or with ordinary electric currents, can yet be accurate. It is because we are there dealing with large numbers. With one electron there is no certainty—we can only talk in terms of probability.

And so we reach a viewpoint which is at least consistent with our everyday experience, and at the same time gives a means of dealing with the ultimate entities of the physical universe. But few would agree that it is a highly satisfactory standpoint. The attempt to unify all our knowledge of the electron has driven us to confess that no primary laws—even of the simplest kind—can be formulated to deal with these ultimate particles. We can only deal, using statistical methods, with large numbers.

We must not leave the situation in that state. Possibly, in our association of ideas there is something unsound—or a faulty premiss. Let us look back again.

We think we know what we mean when we say 'that is a moving particle' such as a speck of dust or a marble.

Its position can be measured in space, and its speed can be measured from spacial changes and time changes. This is simple, as it is based on the most, apparently, fundamental of all our notions—our notions of Space and Time—notions which we have acquired from childhood through association with ordinary objects. Starting from those notions we reached the idea of an electron as a particle, but we found that no law which applied to ordinary bodies like a grain of sand or a billiard-ball could apply to the single electron, although they applied to large collections of electrons. Retracing the argument, it may well be that the ideas of Space and of Time which we use in everyday life are themselves only large-scale, or statistical, notions, and are not the simple fundamental ideas we perhaps thought they were.

A moment's reflection will show that this is not such a strange conclusion. Consider how we get these everyday notions. They are got by dealing not with the ultimate in nature, but by dealing with everyday things, large things, the room, the table, ourselves, and so on. Thus Space to us is a macroscopic, large-scale conception. Why, then should we expect it to apply to the ultimately small? Again, consider our notion of Time. The ordinary idea of Time is something that just 'marches on'. The time factor which occurs in Newtonian mechanics is completely reversible—the equations are equally valid whether time goes on or goes back. In this basic world of the primary laws of Newton, there is no Future and no Past—both are equally possible for all mechanical particles, large or small.

Where then do our ideas of Past and Future come from? Consider a drop of ink falling into a beaker of clear water. We know what happens. The ink slowly spreads through the water, and after a certain interval the whole beaker is uniformly coloured. We believe that no one has ever seen the converse happen—inky water slowly clearing up and finishing as clear water with a drop of ink on its surface, just like a film run backwards. But on the basis only of the classical, primary laws of Newton, that strange phenomenon should be a possibility. As it is, we have never seen it actually happen, and so convinced are we that we never shall, that we label the clear water as being in the past, or earlier, and the coloured water as being later, in the future. Our ordinary ideas of Past and Future actually come from observations just like that—and not from the primary laws of Newton. In other words, our ordinary notion of Time comes from our ordinary experience with ordinary objects, and not from dealing with ultimate particles like electrons and so on. Thus our ordinary notion of Time is a statistical, or macroscopic, or large-scale notion, and is possibly not the simple, basic, fundamental entity we have perhaps thought it to be. But if our notion of Time is a statistical notion, why then should we expect it to apply to a fundamental or basic entity like the electron?

The electron concept has thus brought us face to face with this problem. Upon our present ideas of Space and Time, the ultimate nature of the electron—from Heisenberg's principle—is unknowable. Shall we then leave it at that, or shall we go on by reconsidering all our most cherished, and apparently fundamental, notions of Space and Time? Some physicists, notably Lord Cherwell, consider that Heisenberg's principle of uncertainty is really an expression of the inadequacy of our ordinary notions of Space and Time to describe events on the atomic scale. Therein lies the supreme significance of the electron. It is only by studying such ultimate entities that the investigation of the fundamental structure of Matter and of Space is at all possible. In the electron it is exposed—with ordinary bodies it lies hidden.

The riddle of the ultimate structure of the universe still remains unsolved—but it is now reduced to the problem of the nature of the ultimate particles of physics, and the chief of these is the electron. In the words of Born:[1] 'We have sought for firm ground, and found none. The deeper we penetrate, the more restless becomes the universe. All becomes waves and motion.' However, something extremely important has been achieved, as we are now forced to re-examine our most cherished and fundamental ideas. The end is not yet in sight, but great progress is being made with the new relativistic wave-mechanics applied to the electron concept. And so the good work goes on. For, in his urge to investigate, the scientist is akin to the artist, who has the compelling necessity to express himself, whether in paint, in words, or in music. But underneath it all lies the belief in the uniformity of nature—that is, his faith in an explanation, which one day he will be able to make, to unify all nature.

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[1] *The Restless Universe*, p. 227.

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PRINTED IN
GREAT BRITAIN
AT THE
UNIVERSITY PRESS
OXFORD
BY
CHARLES BATEY
PRINTER
TO THE
UNIVERSITY