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WAVES AND PARTICLES[1]

By Professor GEORGE P. THOMSON

OF THE UNIVERSITY OF ABERDEEN, NON-RESIDENT LECTURER IN CHEMISTRY AT CORNELL UNIVERSITY UNDER THE GEORGE FISHER BAKER FOUNDATION

No one who has been so fortunate as to experience the magnificent reception—surpassing even the usual high standard of American hospitality—which you accord to the lecturers of this foundation could possibly begin his duties without a grateful recognition of such splendid treatment. To Mr. George Fisher Baker, the founder of this lectureship, and to Professor Dennis, to whom falls the arduous duty of administration, I want to express thanks which are out of all proportion to what can be expressed in these few words. This foundation is of inestimable value to the men who are fortunate enough to hold it, in giving them an insight into the working of one of the most progressive universities of this country and an opportunity of becoming personally acquainted with a group of very distinguished men. I have a hard task in attempting to give anything approaching a fair return for these advantages, and I hope you will judge leniently my attempts to do so.

If I break this piece of chalk, then take each of the bits and break them, and so on, is there any theoretical limit to the progress other than that imposed by the coarseness of mechanical appliances? This is a question which has occupied science since the twilight of its earliest dawn.

In the last three or four years opinions have altered as to the best answer to this question. During the first quarter of this century the answer to the question was quite definite. If the piece of chalk is continually broken and rebroken a time comes when the pieces are no longer merely smaller but become different in kind. This stage can not be reached by mechanical breaking, but it can be reached by heat and suitable chemical action. The chalk has been broken into its atoms. In chalk there are three kinds; other sub-

[1] Introductory public lecture.

stances would yield other kinds, and, in all, chemists have distinguished ninety kinds from which all matter is made. These atoms are small. They bear about the same relation to a drop of water that a drop of water bears to the earth. But even here the limit had not been reached. Towards the end of the nineteenth century it had been found possible to break pieces off these atoms: for example, by the violent collision of other atoms. These pieces were always the same. They are called electrons and have now become almost an article of commerce, for they are the working material of the radio valve. The hot filament of the valve gives off electrons as water gives off steam, and the electric forces in the oscillating circuit control the motions of the electrons.

The older view of the electron is best expressed by regarding it as a tiny lump of electricity which had a little mass—less than a thousandth of that of a light atom—as a kind of secondary property of its charge. It was supposed to have a certain extremely minute size, but as a matter of fact the estimate of this size rested on purely theoretical arguments and no one had ever measured it. However, it soon became apparent that each atom contained electrons varying in number from one each to nearly two hundred and fifty each for different kinds of atoms. Thus it was reasonable to suppose that an electron was a good deal smaller than an atom.

Later on—it is difficult to give an exact date—it became clear that there was a second universal constituent and that this was the residue of a hydrogen atom when one electron—the only one—was removed. It has been called the proton. Every atom contains, in its normal state, an equal number of electrons and protons. The protons are much the heavier of the two, but they occupy only a very small region in the center of the atom called the nucleus. This region is so small that the combined nuclei of a man's body would form a barely visible speck. Since the nucleus also contains some electrons these apparently must be at least equally small, and we are left with a picture of matter as mostly emptiness. That such a view is not purely figurative has been shown in a striking manner recently. It seems certain that some stars known as "white dwarfs" are so dense that a cubic inch would weigh a ton. This is still nothing like the density of a nucleus but it shows at least that an ordinary solid must have plenty of gaps if it can be compressed to such an extent. The picture of matter was thus essentially one of discontinuity. It consisted of a number of specks—of a whole number, for an electron or proton can not be split. It is a return to the earliest philosophy, for it was Pythagoras who taught that "all is number."

But there was another side of physics in which continuity was supreme. If you had asked the question "How does one electron act on another," the answer would have been "through stresses in the ether." Now the ether has had a long and checkered history. Ethers of a sort were common in early physics—rather too common. But the ether first acquired an assured status in the scientific world when it became clear that light had to be explained as *waves*. As this introduces the other half of the title of my lecture you will perhaps allow me to dwell on it in some detail.

The obvious thing about light is that it goes in straight lines—as can be seen if you watch light passing into a darkened room through a small hole and tracing out a path as it lights up the motes of dust. Now Newton said that a particle free from force goes in a straight line. It was natural to suppose that light consisted of a stream of particles shot out by the luminous object. Light can be reflected by mirrors and refracted by glass but, superficially at least, these effects can be explained as a rebounding of the light particles, or their deflection by forces at the surface of the glass, as the case may be. Nevertheless, influential men such as the Dutch physicist Huygens suggested in the seventeenth century that light was a form of wave motion. Now sound is wave motion and every one knows that sound will go round corners. So will water waves. How can you explain the rectilinear propagation of light on this view? It is all a question of the wave-length. Even in sound a high-pitched note is not heard well round a corner. If the wave-length of light is small enough rectilinear propagation is all right. Also light does bend very slightly. The really crucial test is what is called interference, the property by which two lights can produce darkness. A special form of this is to take a number of regular spaced wavelets, all derived from one wave. This gives a peculiarly marked effect. The effects of the combined wavelets are strongly concentrated in a few privileged directions and cancel everywhere else.

Light shows this phenomenon to a very marked extent. For example, in the case of the diffraction grating, light scattered from a large number of regularly spaced scratches on a glass or metal surface is found to be concentrated in a few directions, and this effect can be used to measure the wave-length of light with very great accuracy.

The ether was required to carry these light waves. At first it was thought of as a kind of jelly, and Lord Kelvin used immense mathematical skill in finding the very peculiar type of jelly which alone gives exact agreement with the experimental laws of light. Now Faraday long before had regarded electric and magnetic effects as stresses in a medium, and Maxwell showed that the same medium could do double duty, carry electric effects and transmit light. Hertz crowned the theory by actually producing waves by purely electromagnetic processes which had the velocity of light, and in fact were invisible light: "light" whose wave-lengths were to be measured in meters instead of thousandths of a millimeter as are those of the visible kind. I need hardly say that these waves are those now used in radio. Later it was shown—not until 1913 indeed, but logically it comes in here—that X-rays are invisible light, on the other side as it were. Their wave-length is about 10,000 times shorter than that of ordinary light instead of millions of times longer. The way in which this was proved is of interest. To show interference well, one needs an apparatus so exactly shaped that the errors are smaller than the wave-length to be tested. Now X-ray wave-lengths are smaller than most atoms. It is impossible to shape an apparatus exact to an atom. Von Laue got over the difficulty in a very ingenious way. He remembered that in a crystal the atoms are arranged in regular order like soldiers drawn up in close formation. The result is a series of lines like a diffraction grating and about the right distance apart. Actually it is a little more complicated because the atoms are arranged in a solid array, while an ordinary grating is on a plane, but this does not really matter. The result of sending X-rays through a crystal is a diffraction pattern, and in this way the wave-lengths can be found.

So far, then, we have matter made of discontinuous particles, while the interaction is due to a continuous medium which can transmit waves. But now came the difficulties. I will take two selected ones which are enough to show their nature. When light is allowed to fall on a polished metal surface, electrons are thrown out from the metal. Since light is electromagnetic waves and electrons are electrical, it is not surprising that there should be an action of this kind, but the details are all wrong. The speed with which the electrons come out does not depend on the intensity of the light. They come out with just the same speed for the feeblest light as for the strongest, only there are fewer of them. Now if, for example, sea waves are breaking on the beach and rolling the pebbles about, the more violent the waves the farther the pebbles are thrown. If the water waves behaved like light, an almost calm sea would throw a few selected pebbles as violently as a great storm throws them all. This is obviously contrary to one's ordinary conception of waves, and it is equally at variance with the results of a complete mathematical treatment. Moreover, the energy with which the selected electrons appear is so great that they would take hours to absorb it from feeble light, while even with the feeblest light there is no detectable lag between switching on the light and the appearance of the electrons. Obviously something is wrong. Einstein suggested that the light contained units of energy or quanta which behaved practically like particles. When one collides with an electron it gives up its energy to the electron which then can escape from the metal. All the quanta in a given kind of light are the same, but the stronger the light the more numerous they are. The energy of each quantum is the frequency of the light multiplied by a quantity "h," which can be found by measuring the energy of electrons emitted by light of known frequencies. This has been done by Professor Millikan. He finds $h = 6.55 \times 10^{-27}$. Now this is all very well for the photoelectric effect, as the above is called, but what about the diffraction grating? We have just decided that light must be waves and now it turns out to be particles instead, for it is essential for the explanation that the quanta should be so concentrated that one electron can catch a whole quantum. This is the famous photoelectric paradox.

Before I try to answer it, I will describe the other difficulty. Atoms can be made to emit light, and each atom emits its own characteristic wave-lengths. These are clearly a consequence of the structure of the particular atom, presumably of the arrangement of its electrons. Now one theory, and one only, was found capable of explaining these wave-lengths even in general terms. This was the theory due to Neils Bohr according to which the electrons were supposed to move in orbits round the nucleus rather like planets round the sun. But in order to make the theory fit the facts, Bohr had to assume a behavior of the electrons which is quite contrary to ordinary dynamics, and curiously enough the same quantity "h" came in, though in quite a different way. The real trouble was not so much that the electrons obeyed different laws from those of Maxwell and Newton, but that they were not consistent about it. Some of the things they did required the old laws to explain them; others required a new and inconsistent set. Sometimes both had to be used in different parts of the same calculation. The position of a physicist investigating an atom was rather like that of a man trying to make sense of an account of a game which started as golf and suddenly for no apparent reason turned into tennis and then back to golf again. Worse still, as time went on it became clear that the electrons did not play fair even at the game they had for the moment chosen. The results were nearly right but not quite. The only hint was that the quantity "h" came in whenever the atom chose to break the old rules, and this suggested a connection with the photoelectric paradox. The first really successful attempt to solve these difficulties is due to Prince L. deBroglie. He realized that the reason why the electron in the atom seemed to follow two different sets of rules at once was that it was behaving much more like a wave than a particle. Now if you think that you are reading an account of a game played with a ball, when really the reporter was writing about a swimming match, it is not to be wondered at if the report does not make good sense. It is perhaps surprising that the physicists made as much of it as they did. DeBroglie's theory was a mathematical one based on relativity. He reached the conclusion that any moving particle would be accompanied by a wave, and he postulated that this wave controlled the motion of the particle. Instead of Newton's laws of motion (motion in a straight line, acceleration proportional to the force, and so on) this view gives a motion governed by waves. Of course Newton's laws are true in every-day life. This is because a very short wave is indistinguishable in behavior from a particle, and the scale of deBroglie's waves is given by "h," which is a very small quantity. But according to his theory the smaller the particle the longer the wave. For an electron in an atom the wave is quite comparable with the size of the atom, and the behavior of the electron is greatly different from what you would expect of a particle. It has been found in fact that this theory when fully applied mathematically as it has been by Schrödinger and others brings order out of chaos in the explanation of the properties of atoms.

Further, it is capable of dealing with the photoelectric paradox. Granting that there are in fact quanta, or particles, in radiation, they will inevitably be accompanied by waves which will guide them. The quota will appear where the waves are strong; where there are many quanta the light will be intense. In other words, the regions of brightness and darkness will be just those predicted on the wave theory. This way out had indeed been suggested before. It turns the flank of the difficulty by saying that it is the natural way for a particle to behave. But if you accept this you must be prepared to take the consequences. A free electron, such as a cathode ray, should also be guided by waves and should also show diffraction. How could we hope to detect it if it did? Calculation shows that the wave-length of a free electron of manageable energy is of the same order as that of X-rays. Can not we use a method similar to that by which the waves of X-rays have been measured and take advantage of the regular structure of crystals?

Successful experiments on these lines have in fact been made by Dr. Davisson and Dr. Germer in this country and by myself and others in Scotland. In my own experiments a narrow beam of fast electrons, cathode rays, in fact, pass through a very thin film of metal. The metal scatters the electrons, and since metals consist of a number of minute crystals, the scattering occurs predominantly in certain privileged directions, just as is the case with X-rays. Accordingly, if the electron strikes a photographic plate placed somewhere behind the thin film we should expect to get a pattern similar to that produced by X-rays of the same wave-length. This expectation is in fact realized. I have obtained these diffraction patterns from a considerable number of metals. In all cases the patterns are in exact agreement with what is to be expected if they are regarded as the result of diffraction of waves by the known crystal structure of the particular metal used. The patterns are in general formed of concentric rings just like the familiar Debye-Scheerer X-ray powder photographs. From the sizes of the rings it is possible to deduce the wave-length of the waves causing them, and I find in all cases absolute agreement with the theoretical expression due to deBroglie, $\lambda = h/mv$. Thus instead of being scattered irregularly by the metal, it appears that if the film is thin enough it will guide the electrons into the directions which would be taken up by waves diffracted from the crystal structure of the metal.

If you accept the experiments as showing that electrons behave as if guided by a train of waves, you will agree that deBroglie's idea brings a remarkable simplification. Both electrons and light quanta are on the same footing as particles guided by waves. The difficulties of physics in the earlier years of this century were due to ignorance of this dual character. For some reason we had got hold of the wave aspect of light and the particle aspect of electrons, and were running each to the exclusion of the complementary view. It also explains the curiously confusing nature of the difficulties. If we had neglected, say, the wave aspect in each case, all the new facts would have pointed to waves. As it was, some pointed to particles and some, as we now know, to waves.

This dual aspect of things as waves and particles must be very fundamental in the world. There is little doubt that protons would show it also, though experimental proof has so far not been possible. There is even strong, though indirect, evidence that a completed atom has a wave as a whole as well as component waves for its individual electrons. One reason for regarding the duality as really fundamental is that it holds for such different things as electrons and quanta. For in spite of this one point of resemblance they are essentially different. The electron has electric charge and hence is influenced by electric and magnetic forces in a way that the quantum is not. The quantum always goes (*in vacuo*) with a speed of 300,000 kilometers a second. The electron can go with any speed, provided it is less than this. For equal wave-lengths the penetrating power is quite different. These differences make it all the more significant they should both show the same curious duality. The new view is not by any means free from difficulties. To take the most obvious, many electrons form part of each of the atoms of a crystal, yet the experiments I have described essentially involve the idea that the wave of the moving electron is spread over a number of the atoms in the crystal. Have we proved that the part is greater than the whole? I think that even modern physics is not so paradoxical as this. It depends on what you mean by the size of an electron. We can measure the size of atoms in a fairly definite way by finding how many can be packed into a given space of solid. It is rather like measuring the size of shot by counting how many will fill a cartridge case of known volume. Of course we have to allow for possible empty spaces between, but this can be done if we know how they are piled together, and in many cases we do. The sizes are not quite definite; they vary a little with circumstances, but this is not surprising. Suppose that you want to know the size of a tennis ball. It is easy enough to measure it to an accuracy which will satisfy the authorities at Wimbledon that it is legal, but if you were asked to give its diameter to a hundredth of an inch there would be difficulty. Are you going to measure it to the furthest-out hair of the felt? Obviously that is not a very important measurement, but where are you going to stop? There is no sharp edge. Here a rough measurement has a real and useful meaning, but if you try to make it precise beyond a certain point it can be done only by making some arbitrary convention, such as how hard the measuring instrument is to press. This is the case of the atom, but for the electron the size is even less definite. It has not got even an approximate boundary, as far as our present knowledge goes. It is more like a gas which can expand to "fill" (in a sense) any vessel into which it is put, and yet can be compressed into a very small space. When an electron is part of an atom, its waves curl round, as it were, on themselves until it occupies only the atom, and perhaps only a part of that. When it gets free from the atom as a cathode ray, or escapes from the filament of a valve, its waves can uncurl and expand indefinitely. I think, however, that in all cases one must consider it as also having a sort of center, even if this is only a mathematical point. Whenever an electron produces any detectable effect it does so as a particle, and it seems easiest to suppose that even when it is not producing an effect the particle is somewhere round. The best analogy I have been able to find for this view is a gossamer spider.

When this little animal is clinging to the stalk of a plant, it is a small solid object. When it wants to move it shoots out long filaments many times its own length. The wind catches these and wafts it away. I regard the filaments as analogous to the waves which surround the electron, while the body of the spider is analogous to the central point. One can press the analogy further. If the wind carries the spider so that one of its filaments is caught in an obstacle, the spider will be swung around and its path deflected although its body has not hit anything solid. In just the same way with the electron, if its waves pass over an obstacle, say an atom, the direction is modified and this modification is transmitted back through the wave system to the electron itself. If we suppose that the electron is constrained always to move in a way determined by the waves in its immediate neighborhood, the motion of the electron itself will thus be modified. The waves thus act as a kind of intermediary between the disturbing objects and the electron itself. The electron goes where the waves in its immediate neighborhood carry it, just as the spider is pulled by the parts of the filaments which are actually attached to it. But the form of the waves, near the electron, is determined by events at a distance, whose effects are propagated through space in the form of waves.

A question that inevitably arises is—what is the medium which transmits electron waves? I am sorry that I can give no entirely satisfactory answer. For the first time, physics is faced with waves in empty space which do not fit into the ordinary series of ether vibrations. All the ether vibrations differ only in wave-length; if the wave-length is given, the kind of "light" is fixed. The electron waves have varying wave-lengths depending on the speed of the electron, but they usually fall in a region of wave-lengths which is already appropriated by X-rays. As we have seen, they are certainly not the same as X-rays. One must suppose some other medium, or at least that the ordinary ether is in some way profoundly modified by the presence of the electron. It is possible that they are waves in a "subether." But it is not a very attractive idea to have two ethers filling space, especially as the waves of protons, if they exist, would demand yet a third. Space is getting overcrowded. Other suggestions are to regard the waves as a kind of mathematical abstraction, a sort of ghost waves. The whole question is getting very metaphysical. Perhaps a simple physicist may be content as long as the waves do their job of guiding the electron, and it is possible that, after all, the question will ultimately be seen to be meaningless.

Whatever the medium is, the new wave conception has altered the view we take of the best answers to the question with which I began this lecture. Matter is still supposed made of discrete units, but instead of these units moving by laws which concern them alone as did the laws of Newtonian dynamics, we have had to introduce laws based on waves. Now a wave is essentially a continuous thing, even if the continuity is only mathematical. It is spread through space, not divided into little lumps. So although the older belief in the discontinuity of matter still holds, it has lost some of its rigidity; continuity has crept in by the back door.

The idea of the ether has also changed. The sole function left it is to guide the quanta; they do the work. The picture of light as waves breaking on a shore of matter, and thus disturbing it, is replaced by one of a stream of bullets which affect only the particular objects which they hit. The bullets, it is true, do not move quite as ordinary bullets would; they are directed by the waves, but all the effects are bullet effects, not wave effects.

We have seen that Newtonian mechanics needs modification; that it is a simplification which is permissible only when the wave-length is very small. This of course does not detract from its practical value in every-day life and in astronomy, nor from our estimate of the genius which gave it a form which has satisfied two and a half centuries. On the contrary, the new developments, as far as they concern light, which I have tried to explain to you at such length, are much better expressed in the words of Newton's Optics.

> Those that are averse from assenting to any new discoveries but such as they can explain by an hypothesis, may for the present suppose, that as stones by falling upon water put the water into an undulatory motion, and all bodies by percussion excite vibrations in the Air; so the Rays of Light excite vibrations in the refracting Medium or Substance . . . that the vibrations thus excited are propagated in the refracting or reflecting Medium or Substance, much after the manner that vibrations are propagated in the Air for causing Sound, and move faster than the Rays so as to overtake them . . . and that every Ray is successively disposed to be easily reflected or easily transmitted by every vibration which overtakes it. But whether this Hypothesis be true or false I do not here consider.

After being regarded for generations as an artificial attempt to save a dying theory, we have proved this guess of Newton's to be a supreme example of the intuition of genius.

THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

THE DES MOINES PRIZE

THE approach of the annual meeting of the American Association and associated societies, which is to occur this year at Des Moines, Iowa, between December 27 and January 2, attracts attention to the annual award of the American Association prize. As most readers know, this thousand-dollar prize is awarded annually to the author of a notable contribution to science presented at the annual meeting. The award is made possible through the generosity of a member of the association who prefers that his name shall not be revealed. In the establishment of the annual prize it was the aim of the donor and of the association to aid some of the younger investigators in the continuation of studies by which they have already made valuable contributions. While the award of course constitutes a notable honor, yet it is to be considered primarily as an aid to further productive study.

Membership in the association is not required to render an author eligible to consideration in the awarding of the prize, but the prize must always be awarded to the author of a paper presented at the meeting and announced in the general program, which includes the programs of all the special societies that take part in the annual meeting. Because contributions in different fields of science can not be quantitatively compared with respect to value and importance, it is expressly stated that the committee on prize award shall make no attempt to select the *best* or *most* notable paper presented at the meeting. The committee is asked simply to select a paper that is noteworthy. It has also been provided that the prizes at two consecutive meetings shall not be awarded in the same field of science.

There is no open competition for this prize and authors are not to submit manuscripts nor to make applications to those who have the responsibility of the award. Any paper presented at the meeting may be considered, as has been said. It should be noted, however, that the Press Service of the American Association requests from the authors two copies of every paper to be presented at any meeting and needs to have these at least a week or two before the opening of the meeting. It is desirable that the representatives of the press should have access to the manuscripts of all papers long before they are to be presented and the Press Service, of which Austin H.