II

WHAT IS LIGHT?

AS long ago as the seventeenth century, Newton defended the view that light consists of streams of little particles, shot with tremendous speed from a candle or the sun or any other source. At the dawn of the nineteenth century, however, experiments were performed which gave positive evidence that light consists of waves. Maxwell interpreted them as electromagnetic waves, and in such terms we have ever since been explaining light rays, X-rays, and radio rays. We have measured the length of the waves, their frequency and other characteristics, and have felt that we know them intimately. Very recently, however, a group of electrical effects of light has been discovered for which the idea of light waves suggests no explanation, but whose interpretation is obvious according to a modified form of Newton's old hypothesis of light projectiles.

WHAT WE MEAN BY "LIGHT"

When the physicist speaks of light he thinks not only of those radiations which affect the eye, he refers rather to a wide range of radiations, similar to light in essential nature, but differing in the quality described variously by the terms color, wave-length, or frequency. At one end of this series of radiations are the wireless, or radio rays, with which in recent years we have become so familiar. There is an important point regarding these rays to which I should like to call attention. When one strikes the strings of a mandolin, they are set into vibration, and produce in the surrounding air the waves which affect our ears and cause the sensation of sound. Investigation shows that the sound waves in air vibrate with the same frequency—the same number of times per second—as do the strings on the mandolin. In precisely the same way, when an electrically charged condenser is discharged an oscillation of the electric charge is set up which gives rise to electric waves, just as the vibrating string produced sound waves. That is, the emitted electric waves have the frequency of the oscillating source.

Though visible light is known to be essentially the same kind of thing as these electric waves, we have long sought in vain for any oscillator which would emit light waves having the same frequency as that of the oscillating source. It was only when Heisenberg introduced a new kind of mechanics, differing radically from the classical ideas of Newton, that we found that the atom vibrates with certain "overtones" whose frequency is that of the light waves which come from it. This is one of the serious difficulties with the wave conception of light, which could only be solved by a fundamental change in our ideas regarding how things work.

Measured in terms of the length of a wave, from one crest to the next, electric waves extend from many miles in length, down through the radio waves of say 300 meters, to the very short waves resulting from tiny sparks, which may be no more than a tenth of a millimeter in length. These rays overlap in wave length the longest heat waves radiated by hot bodies, and may be detected and measured by the same instruments. A familiar source of such heat rays is the reflector type of electric heater, the kind that warms one side of us in a chilly room. The greater part of these heat rays are intermediate in wave-length between the shortest electric waves and visible light. Such a heater, however, glows a dull red, meaning that its rays extend into the visible regions.

Ordinary light, such as that from the sun, may be spread out into a spectrum by allowing it to pass through a prism. Beyond the red end of the spectrum lie the heat rays. Indeed, if we should place a radiometer just beyond the red end of the spectrum, we should find it strongly affected by the heat rays from the sun. The question arises, are there similar radiations beyond the violet which we are unable to see?

Though the eye is not sensitive to light in this region of the spectrum, a photographic plate placed beyond the violet receives an impression, and the radiation in this region can be made visible by placing in its path some fluorescent substance, such as petroleum oil. These are the ultra-violet rays, of which we have recently heard so much in connection with summer sunshine and the prevention of rickets.

As one goes farther into the ultra-violet, the rays become rapidly absorbed by air, and can be studied only in a vacuum. But at still shorter wave-lengths the rays are again less readily absorbed as we approach the region of X-rays. Just as in the case of the ultra-violet light, these rays do not affect our eyes. They do however affect a photographic plate or produce fluorescence just as does the ultra-violet light. That X-rays are of the same nature as light is shown by the fact that we have been able to refract and reflect them, to polarize and to diffract them. They are indeed light of ten thousand times shorter wave-length.

One of the most important properties of X-rays is their ability to ionize air and make it electrically conducting. This is shown for example by the fact that a charged electroscope when exposed to X-rays is promptly discharged. This is due to the breaking up by the X-rays of the oxygen and the nitrogen atoms of the air. Precisely the same thing happens when the atoms in one's body are exposed to X-rays. It is this which makes possible X-ray therapy.

Such ionization can also be produced by the gamma rays from radium. These rays are more penetrating even than X-rays. Whereas X-rays may be half absorbed in an inch of water, it takes a foot of water to absorb half of a beam of gamma rays, corresponding to the much shorter wave-length of the gamma rays.

But the end is not yet. There exists a kind of highly penetrating radiation which is especially prominent at high altitudes, and is supposed to come from some source outside the earth. These *cosmic rays*, as they are called, will penetrate ten or twenty feet of water before they are half absorbed. If these rays are of the same nature as visible light, they must be of yet much shorter wave-length than the gamma rays from radium.

Thus from cosmic rays, with a wave-length of 2×10^{-13} cm. to electric waves 2×10^{6} cm. long there is found to be a continuous spectrum of radiations, of which visible light occupies only a very narrow band. The great breadth of this wave-length range will perhaps be better appreciated if we expand the scale until the wave of a cosmic ray has a length equal to the thickness of a post card. The longest wireless wave would on this scale extend from here to one of the nearer fixed stars.

When the physicist speaks of light, he refers to all the radiations included in this vast range. We believe that they are all the same kind of thing, and that anything which may be said about the nature of the rays in one part of this region is equally true of the rest.

THE WAVE PROPERTIES OF LIGHT

There are many ways in which light acts like a wave in an elastic medium. Such elastic waves move with a speed which is the same for all wave-lengths and all intensities, just as does light. Waves, like light rays, can be reflected and refracted. The polarization of light is a property characteristic of the transverse waves in an elastic solid. It is true that if one examines the constancy of the speed of light in detail, difficulties arise; for it is found that its speed is the same relative to an observer no matter how fast the observer is going. This would not be true if light were a wave in an ordinary elastic medium. Maxwell's identification of light as electromagnetic waves, however, removes this difficulty.

The crucial test for the existence of waves, however, has always been that of diffraction and interference. Imagine that a series of ripples on a pond is passing through the openings of a grid. The crests of the emerging wavelets recombine to form a new wave going straight ahead. But in addition, the wavelet just emerging from one opening may combine with the first wave from the next opening, the second from the next, and so on, forming a new wave-front inclined at a definite angle to the first. The angle between these two waves is determined by the distance between the successive waves—the wave length—and by the distance between successive openings in the grid.

That such a variety of wave formation is not purely imaginary is shown in figure 1, which is a photograph of ripples on the surface of mercury, taken after they have passed through a comb-like grid. Notice how one group of waves combines to form a wave-front going straight ahead. But in addition, on either side of the central beam we find

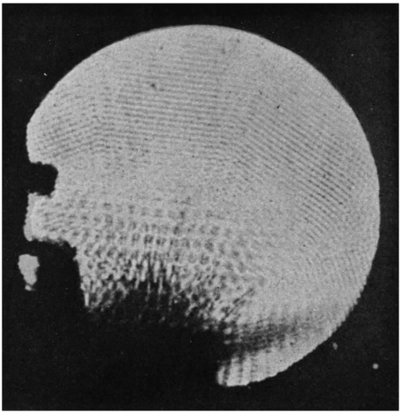

Fig. 1

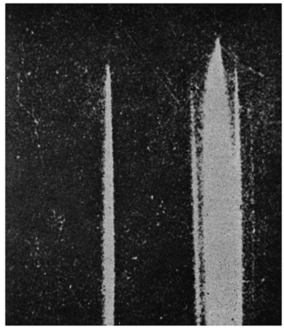

Fig. 2

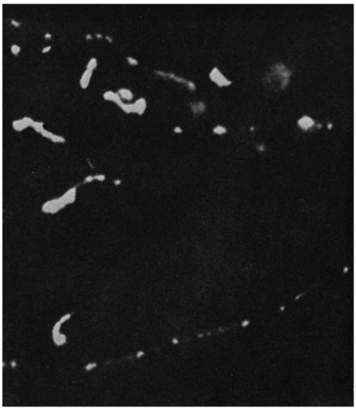

Fig. 3

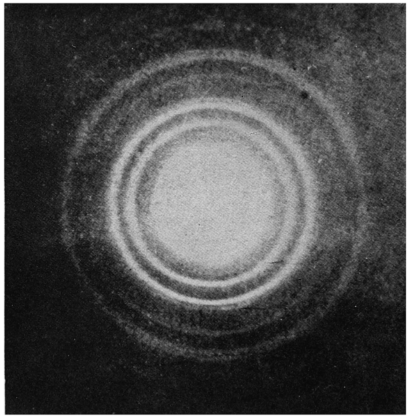

Fig. 4

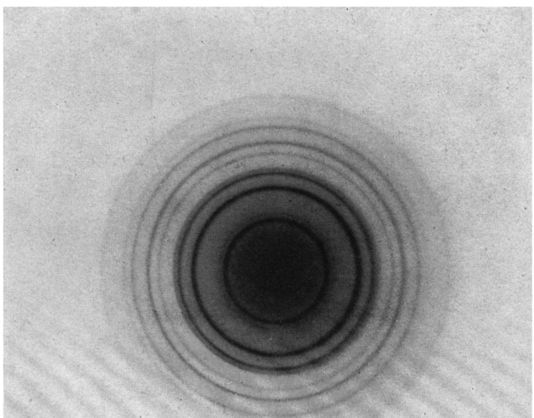

Fig. 5

two beams forming where parts from successive openings in the grid differ by one wave-length. Out at a larger angle we see even a second order of the diffracted beam where there is a difference of two wave-lengths between the ripples coming from adjacent openings.

If we were unable to see the successive waves, but knew the kind of grid through which the ripples had passed, not only could we say that this is the way in which the beam should be split up if it consists of waves, but we could even tell what the wave-length of the ripples must be in order to give these particular angles to the diffracted beam.

During the present lecture we performed the same experiment with a beam of light. A set of some 200 vertical lines was photographed onto a lantern slide, forming a grid through which a beam of light was made to pass. When this grid was placed in front of the lens of the projection lantern, the original line of light projected on the screen was split into three, a bright one in the center—the direct ray—and a diffracted ray on either side. It was just as in the case of the mercury ripples passing through the grid. A grid with about 300 lines to the inch was then placed over the lens, and the separation of the lines was much greater. The outer edges of the diffracted lines were red and their inner edges blue. This means that red light is of the greater wave-length. In fact it would have been possible from this experiment to tell what the wave-length of light is: The distance from the central image to the diffracted image is to the distance from the lantern to the screen as the wave length of the light is to the distance between the lines on the grating. When one carries through the calculation, he finds that the wave-length of the light is about a fifty-thousandth of an inch.

Precisely similar experiments can be done with X-rays. Only in place of the projection lantern we use an X-ray tube and a pair of slits. The slide with the lines photographed on it is replaced by a polished mirror on which lines are ruled fifty to the millimeter. Instead of the screen we use a photographic plate. A typical resulting photograph is shown in Fig. 2. When the ruled mirror is withdrawn, we have the single vertical line *D*. With the grating in place, we see a bright central reflected image *O* with companions on either side. Thus X-rays can also be diffracted, and must, therefore, like light, consist of waves.

LIGHT CONSISTS OF PARTICLES

For a hundred years no one had seriously questioned the truth of the wave theory. At the close of the last century even the difficulty of supplying a suitable oscillator to give rise to the light waves seemed about to disappear through the discovery of electrons. But in 1900 Planck published the results of a long study of the problem of radiation of heat and light from a hot body. This difficult theoretical study, which has stood the test of time, showed that if a body when heated is to become first red hot, then yellow, and then white, the oscillators in it which are giving out the radiation must not radiate continuously as the electromagnetic theory would demand. They must rather radiate suddenly little portions of energy. The amount of energy in each portion must further, according to Planck, be proportional to the frequency. This is the origin of the celebrated "quantum" theory.

On account of the difficult reasoning involved in Planck's argument, his conclusions carried weight only among those who were especially interested in theoretical physics. Among these was Einstein, who called attention to the fact that Planck's conclusions would fit exactly with the view that the radiation was not emitted in waves at all, but as little particles, each possessing a portion of energy proportional to the frequency of the oscillator, as Planck had assumed.

EINSTEIN AND THE PHOTOELECTRIC EFFECT

An opportunity to apply this idea was afforded by the photoelectric effect. It is found that when light as from an arc falls upon certain metals, such as zinc or sodium, a current of negative electricity in the form of electrons escapes from the metallic surface. This photoelectric effect is especially prominent with X-rays, for these rays eject electrons from all sorts of substances.

The most remarkable property of these photoelectrons is the speed at which they move. X-rays are produced when cathode electrons bombard a metal target inside the X-ray tube. Let us suppose that the cathode electron strikes the target at a speed of a hundred miles a second—quite a normal speed for these little particles. The resulting X-ray, after passing through the walls of the tube and perhaps a block of wood, may eject a photoelectron from a metal plate placed on the far side. The speed of this photoelectron is then found to be almost as great as that of the original cathode electron.

The surprising nature of this phenomenon can perhaps be emphasized by an allegory. When I was a young lad, my father used to take our family to a lake in northern Michigan. My older brother, with several of the older boys, built a diving pier beyond the point half a mile away from camp, where the water was deep. Fearing lest something would happen, mother would not allow us younger boys to swim in this deep water. So we built a diving pier of our own in the shallower water in front of camp. It so happened, one hot, calm, July day, that my brother dove from his diving board into the deep water. The ripples from the resulting splash must have spread out over the lake. By the time they had gone around the point to where I was swimming, they were of course much too small to notice. You can imagine my surprise, therefore, when these insignificant ripples, striking me as I was swimming under our diving pier, suddenly lifted me from the water and set me on the diving board!

Of course this story is impossible. Yet if it is impossible for a water ripple to do such a thing, it is just as impossible for an ether ripple, sent out when an electron dives into the target of an X-ray tube, to jerk an electron out of a second piece of metal with a speed equal to that of the first electron.

It was considerations of this kind that showed to Einstein the futility of trying to account for the photoelectric effect on the basis of waves. He saw, however, that this effect might be explained if light and X-rays consist of particles. These particles are now commonly called *photons* or *light quanta.* The picture of the X-ray experiment on this view would be that when the electron strikes the target of an X-ray tube, its energy of motion is transformed into a photon, that is, a particle of X-ray, which goes with the speed of light to the second piece of metal. Here the photon gives up its energy to one of the electrons of which the metal is composed, and throws it out with an energy of motion equal to that of the first electron.

In this way Einstein was able to account, in a very satisfactory way, for the phenomenon of the ejection of electrons by light and X-rays.

PECULIAR X-RAY ECHOES

Even more direct evidence that light consists of particles has come from a study of X-ray echoes. If you hold a piece of paper in the light of a lamp, the paper scatters light from the lamp into your eyes. In the same way, if the lamp were an X-ray tube, the paper would scatter X-rays into your eyes. If light and X-rays are waves, scattered X-rays are like an echo. When one whistles in front of a wall, the echo comes back with the same pitch as the original sound. This must be so; for each wave of the sound is reflected from the wall, as many waves return as strike, and the frequency or pitch of the echoed wave is the same as that of the original wave. In the case of scattered X-rays, the echo should similarly be thrown back by the electrons in the scattering material, and should likewise have the same pitch or frequency as the incident rays.

A few years ago we measured the pitch of some X-ray echoes, using an X-ray spectrometer. We found that though a part of the scattered rays is of the original wave-length, a greater part is of increased wave-length. This would correspond to a lower pitch for the echo than for the original sound.

As we have seen, this change in wave-length is contrary to the predictions of the wave theory. If we take Einstein's idea of X-ray particles, however, we find a simple explanation of the effect. On this view we may suppose that each photon of the scattered X-rays is deflected by a single electron. Picture to yourselves a golf ball bouncing from a football. A part of the golf ball's energy is spent in setting the football in motion. Thus the golf ball bounces off having less energy than when it struck. In the same way, the electron from which the X-ray photon bounces will recoil, taking part of the photon's energy, and the deflected photon will have less energy than before it struck the electron. This reduction in energy of the X-ray photon corresponds, according to Planck's original quantum theory, to a decrease in frequency of the scattered X-rays, just as the experiments show. In fact, the theory is so definite that it is possible to calculate just how great a change in frequency should occur, and the calculation is found to correspond accurately with the experiments.

RECOILING ELECTRONS

If this explanation is the correct one, it should however be possible to find the electrons which recoil from the impact of the X-ray particles. Before this theory of the origin of scattered X-rays was suggested, no such recoiling electrons had ever been noticed. Within a few months after its proposal, however, C. T. R. Wilson succeeded in photographing the trails left when electrons in air recoil from the X-rays which they scatter. Figure 3 shows one of his typical photographs. The X-rays are going from left to right. At top and bottom you notice the long trails left by two photoelectrons which have taken up the whole energy of a photon. In between are a number of shorter trails, all with their tails toward the X-ray tube. These are the electrons which have been struck by flying X-ray photons. Some have been struck squarely, and are knocked straight ahead. Others have received only a glancing blow, and have recoiled at an angle. Thus we have observed not only the loss in energy of the deflected photons, as shown by the lowering in pitch of the X-ray echo, but we have found also the recoiling electrons from which the photons have bounced.

In order, however, to satisfy ourselves by a crucial test whether X-rays act like particles, an experiment was devised which would enable one to follow both the photon as it is deflected by an electron and the motion of the recoiling electron. So feeble a beam of X-rays was used that on the average only one or two recoil electrons appear at a time. Let us suppose that the first electron struck by the X-ray particle recoils downward. This must mean that the X-ray particle has been deflected upward. If this X-ray should strike another electron before it leaves the chamber, this event must occur in a definite upward direction. It cannot occur on the same side as the recoil electron. If, however, the X-ray is a wave, spreading in all directions, there is no more reason why the second electron associated with the scattered ray should appear on one side than on the other. A series of photographs which show the relation between the direction of recoil of the first electron and the location of the second electron struck by the scattered X-ray thus affords a crucial test between the conception of X-rays as spreading waves and as particles.

From a large number of photographs taken in this manner it has become evident that *an X-ray is scattered in a definite direction like a particle.*

But if X-rays, so also the rest of the family of electromagnetic radiations, for they are all the same kind of thing. It would thus seem that by these experiments Einstein's notion of light as made of particles is established.

THE PARADOX OF WAVES AND PARTICLES

We thus seem to have satisfactory proof from our diffraction experiments that light consists of waves. The photoelectric and scattering experiments afford equally satisfactory evidence that light consists of particles. How can these apparently conflicting ideas be reconciled?

ELECTRON WAVES

Before attempting to answer this question, let me call to your attention the fact that this dilemma applies not only to radiation but also in other fundamental fields of physics.

When the evidence was growing strong that radiation, which we had always thought of as waves, had also the properties of particles, Prince L. de Broglie of Paris asked himself, may it not then be possible that electrons, which we know as particles, have the properties of waves? An extension of Planck and Einstein's quantum theory enabled him to calculate what the wave-length corresponding to a moving electron should be. In photographs such as figure 3 we have ocular evidence that electrons are very real particles indeed. Nevertheless, de Broglie's seemingly absurd suggestion was promptly subjected to experimental test by Davisson and Germer at New York, and later by Thomson at Aberdeen, and others.

You will recall that our crucial evidence for the wave character of light was the fact that light could be diffracted by a grating of lines ruled on glass. X-rays were diffracted in the same way; but before this had been shown possible, it was found that X-rays could be diffracted by the regularly arranged atoms in a crystal. The layers of atoms took the place of the lines ruled on glass. X-rays may be passed through a pair of diaphragms and a mass of powdered crystals which diffract them, and produce an image on a photographic plate. In figure 4 is shown a photograph thus obtained, when X-rays pass through a sheet of aluminum which consists of minute aluminum crystals. The diffraction haloes around the central image form one of the best proofs we have of the wave nature of X-rays.

G. P. Thomson has performed a precisely similar experiment, except that the X-ray beam was replaced with a stream of electrons, and the sheet of aluminum with a gold leaf. A photograph thus obtained is shown in figure 5. Here again are the central image and several haloes produced now by diffracted electrons. If figure 4 demonstrated the wave character of X-rays, does not figure 5 prove equally definitely the wave character of electrons?

In a similar way recent experiments by Dempster have shown that protons can be diffracted by crystals. Johnson has diffracted neutral hydrogen atoms. Stern has done the same with helium atoms and hydrogen molecules. It would seem that all of these "particles" have wave characteristics if an appropriate experiment is performed to detect them.

We are thus faced with the fact that the fundamental things in nature, matter and radiation, present to us a dual aspect. In certain ways they act like particles, in others like waves. The experiments tell us that we must seize both horns of the dilemma.

A SUGGESTED SOLUTION

There has gradually developed a solution of this puzzle, which, though at first rather difficult to grasp, seems to be free from logical contradictions, and capable of describing the phenomena which our experiments reveal. The point of departure is the mathematical proof that the dynamics of a particle may be expressed in terms of the propagation of a group of waves. That is, the particle may be replaced by a wave train—the two, as far as their motion is concerned, may be made mathematically equivalent. The motion of a particle such as an electron or a photon in a straight line is represented by a plane wave. The wave-length is determined by the momentum of the particle, and the length of the train by the precision with which the momentum is known. In the case of the photon, this wave may be taken as the ordinary electromagnetic wave. The wave corresponding to the moving electron is usually called by the name of its inventor, a de Broglie wave.

It is not usually possible to describe the motion of either a beam of light or a beam of electrons without introducing both the concepts of waves and particles. There are certain localized regions in which at a certain moment energy exists, and this may be taken as a definition of what we mean by a particle. But in predicting where these localized positions are to be at a later instant, a consideration of the propagation of the corresponding waves is usually our most satisfactory mode of attack. According to this theory, electromagnetic waves and the de Broglie waves are both waves of probability. That is, they tell where the particles probably are.

Consider as an example the diffraction pattern of a beam of light or of electrons, reflected from a ruled grating, and falling on a photographic plate. In the intense portion of the diffraction pattern there is a high probability that a grain of the photographic plate will be affected. In corpuscular language, there is a high probability that a photon or electron, as the case may be, will strike this portion of the plate. Where the diffraction pattern is of zero intensity, the probability of the particle striking is zero, and the plate is unaffected. Thus there is a high probability that a photon will be present where the intensity of the electromagnetic wave is great, and a lesser probability where this intensity is smaller.

It is a corollary that the energy of the radiation lies in the photons and not in the waves. For we mean by energy the ability to do work, and we find that when radiation does anything it acts in particles.

Thus we find from our experiments on diffraction and interference that light consists of waves. The photoelectric effect and the scattering of X-rays give equally convincing reasons for believing that light consists of particles. For centuries it has been supposed that the two conceptions are contradictory. Goaded on, however, by the obstinate experiments, we seem to have found a way out. Whenever the light does anything it works as particles; but in predicting where the particles are to appear we continue to think of the light propagated as waves.