of action should be introduced cannot be exactly defined. No wonder, therefore, that the classical theories even now oppose with all their might the recognition of this intruder, and that years must elapse before the dual assimilation process is complete.

There can be no doubt that the time will come when the chemical atomic weights, as well as the elementary quantum of action, whatever its name or form, will constitute an integral part of general dynamics. Then physical research will be unable to rest until the theory of heat and radiation has been welded into one united theory with mechanics and electro-dynamics.

No = MECHANICS AND ENERGY.

The Nature of Light

One of the most important branches of work of this society (the *Kaiser-Wilhelm-Gesellschaft*) is the maintenance of a research laboratory for natural science. The society has, however, discovered the old truism that in its own sphere, as in all spheres of work, knowledge must precede application, and the more detailed our knowledge of any branch of physics, the richer and more lasting will be the results which we can draw from that knowledge.

In this respect, of all the branches of physics, there is no doubt that it is in optics that research work is most advanced, and, therefore, I am going to speak to you about the *Nature of Light*. I shall doubtless mention much that is familiar to each of you, but I shall also deal with newer problems still awaiting solution.

The first problem of physical optics, the condition necessary for the possibility of a true physical theory of light, is the analysis of all the complex phenomena connected with light, into objective and subjective parts. The first deals with those phenomena which are outside, and independent of, the organ of sight, the eye. It is the so-called light rays which constitute the domain of physical research. The second part embraces the inner phenomena, from eye to brain, and this leads us into the realms of physiology and psychology. It is not at all self-evident, from first principles, that the objective light rays can be completely separated from the sight sense, and that such a fundamental separation involves very difficult thinking cannot better be proved than by the following fact. Johann Wolfgang von Goethe was gifted with a very scientific mind (though little inclined to consider analytical methods), and would never see a detail without considering the whole, yet he definitely refused, a hundred years ago, to recognize this difference. Indeed, what assertion could give a greater impression of certainty to the unprejudiced than to say that light without the perceptive organ is inconceivable? But, the meaning of the word light in this connection, to give it an interpretation that is unassailable, is quite different from the light ray of the physicist. Though the name has been retained for simplicity, the physical theory of light or optics, in its most general sense, has as little to do with the eye and light perceptions as the theory of the pendulum has to do with sound perception. This ignoring of the sense-perceptions, this restricting to objective real phenomena, which doubtless, from the point of view of immediate interest, means a considerable sacrifice made to pure knowledge, has prepared a way for a great extension of the theory. This theory has surpassed all expectations, and yielded important results for the practical needs of mankind.

A very significant discovery relating to the physical nature of light rays was that light, emanating from stars or terrestrial sources, takes a certain measurable time to travel from the position of the source to the place at which it is observed. What is this something which spreads through empty space and moves through the atmosphere at the enormous speed of 300,000 kilometres per second? Isaac Newton, the founder of classical mechanics, made the most simple and obvious assumption that there are certain infinitesimally small corpuscles which are sent out in all directions with that velocity from a source of light, e.g. a glowing body. These particles are different for different colours. This provides a striking proof that a high authority can exercise a hindrance to the development of even this most exact of all natural sciences, for Newton's emanation theory was able to hold the field for a whole century, although another distinguished investigator, Christian Huygens, had from the first opposed it with his much more suitable undulation theory. Huygens did not place the velocity of light on a par with that of wind, as Newton did, but on a par with the velocity of sound, in which the velocity of propagation is something quite different from that of air movements. Consider the air surrounding a sounding instrument or the surface of water into which a stone has been thrown. It is not the air or water particles themselves that spread out in all directions with equal velocity, but the intensification and rarefaction, or wave crests and troughs; in other words, it is not with matter itself, but with a certain state of matter that we are concerned. To this end, Huygens formulated an ideal substance, uniformly occupying all space, as a foundation for his theory. This is the light-ether, the waves of which produce light perceptions in the eye, as air waves give rise to sound perceptions in the ear. The wave-length or frequency determines the colour in the same manner as it determines the pitch in sound. After a bitter controversy, Huygens's theory ultimately superseded that of Newton. This was due to the fact, amongst many others, that when two light rays of the same colour are superposed and made to travel on the same path, the intensities are not always simply additive, but under certain conditions the intensity is decreased and may even vanish. This last phenomenon, interference, can be straightway explained on Huygens's assumption that in every case the wave crests of one ray coincide with the wave troughs of the other ray. Newton's emanation theory naturally contradicts this, since it is impossible for two similar corpuscles travelling with the same speed in the same direction to neutralize one another.

A more significant fundamental view of the nature of light was obtained through the discovery of the identity of light and heat rays, and this was the first step on the way towards the complete separation of the science from the sense-perceptions. The cold light rays of the moon are physically of exactly the same nature as the black heat rays emitted from a stove, except that they are of much shorter wavelength. It is only natural that this assertion at first excited much discussion, and it is characteristic that Melloni, who played a great part in the verification of this fact, set out originally to disprove it. It must be remembered that here, as in all inductive results, a logical and conclusive proof cannot be given; it can only be shown that all laws which hold for light rays, namely those of reflection, refraction, interference, polarization, dispersion, emission, and absorption, are also true for heat rays. Whoever refuses to admit the identity of the two kinds of rays in spite of this, could certainly never be accused on this account of a logical fallacy; for he would always maintain that it is still possible in the future for an essential difference to be discovered. The practical weakness of his position is that he is, consequently, compelled to renounce a series of important conclusions immediately deduced from the theory of identity. He cannot, for example, maintain that moonbeams also carry heat, though this fact would, at present, appear indubitable to all rational physicists, though it has not been specifically proved.

Having accepted the identity of light and heat rays, there is no difficulty in connecting the infra-red rays with the chemically active ultra-violet rays at the other end of the spectrum. It was some time later that it was realized that this connection of different kinds of rays was capable of great extension, on both sides of the spectrum. Before such an advance could come about, as a preliminary, a transition from the mechanical to the electro-magnetic theory of light was necessary.

In spite of diversity of view, Newton, Huygens, and all their immediate successors were agreed that the clear understanding of the nature of light must be sought in the fundamentals of mechanical science, and this point of view was greatly stimulated by the strengthening of the mechanical theory of heat due to the discovery of the principle of conservation of energy. It is necessary for the explanation of polarization that ether oscillations are not longitudinal, moving in the direction of propagation, like air movements in a pipe, but are transversal, perpendicular to the direction of propagation, like those of a violin string. But one could get no nearer the nature of these oscillations from the laws of mechanics and elasticity. The more elaborate the hypotheses founded on the mechanical theory of light, whether ether was assumed to be continuous or atomic, the more evident became this inadequacy. At this stage, in the middle of the last century, came James Clerk Maxwell, with his bold hypothesis that light was electro-magnetic. His theory of electricity led him to the conclusion that every electrical disturbance moved from its source through space in waves with a

velocity of 300,000 kilometres per second, and the coincidence of this figure, obtained from purely electrical measurements, with the magnitude of the velocity of light, led him to consider light as an electro-magnetic disturbance. The only proof of the correctness of this view lies in the fact that all deductions made from it agree with observation. The fundamental advance associated with his suggestion lies in the enormous simplification of the theory and in the number of results that can be immediately derived from it.

Now, the nature of electro-magnetic phenomena is no more intelligible than that of optical phenomena. To belittle the electro-magnetic theory of light, on the ground that it simply replaces one riddle by another, is to misunderstand the meaning of the theory. For its importance rests on the fact that it unites two branches of physics, which previously had to be treated as independent, and that, therefore, all theorems which are valid for one branch, are applicable to the other—a result which the mechanical theory of light did not, and could not, give. Before the introduction of the electro-magnetic theory, physics was divided into three separate branches—mechanics, optics, and electro-dynamics, and the unification of these is the ultimate and greatest aim of physical research. Though optics cannot be associated with mechanics, it combines completely with electro-dynamics, and thus the number of independent branches has been reduced to two—the penultimate step towards the unification of the physical world picture. When and how the last step will be made, the linking up of mechanics and electro-dynamics, cannot be said, and though many clever physicists are at present occupied with this question, the time does not yet seem ripe for the solution. However, the original mechanical comprehension of Nature, which will allow the coalescing of mechanics and electro-dynamics, has now been thrust into the background in the minds of most physicists, since it regards ether, or, if ether is not sufficient, some substitute as the medium of all electrical phenomena. That which has harmed it most is the result, deduced from Einstein's theory of relativity, that there can be no objective substantial ether, i.e. one independent of the observer. For, if that were not so, then when we consider two observers moving relative to one another in space, one at most could correctly assert that he was at rest relative to the ether, whereas, by the theory of relativity, each of the two could do so equally correctly.

What Maxwell could only prophecy, Heinrich Hertz was able to verify a generation later, when he showed how to produce the electro-magnetic waves calculated by Maxwell, and thereby ensured the final acceptance of the electro-magnetic theory of light, according to which electric waves only differ from heat and light rays in that they have very much greater wave-length. If the optical spectrum were extended on the side of the slow oscillations in a manner undreamt of at one time, the extension would be of equal importance with that made on the other side of the spectrum through the discovery of the Röntgen rays and the appreciably faster so-called Gamma rays of radio-active substances. These rays, too, have the character of light waves, and are electro-magnetic oscillations, but have a very much shorter wave-length. Laue's very recent discovery of interference phenomena with Röntgen rays has confirmed the belief that they obey the same laws. It is remarkable how simply and quietly the transition from the mechanical to the electro-magnetic theory was made in physical literature. This is a good example of the fact that the kernel of a physical theory is not the observations on which it is built, but the laws to which they give rise. The fundamental equations of optics remain unaltered: they have always been in agreement with observation, but they are no longer to be interpreted mechanically (although they were thus derived) but electro-magnetically, and this has increased enormously their range of application.

This is not the first time that an important goal has been reached by a path which has afterwards been proved to be untrustworthy. It would have been possible to seek a solution by supposing that the theory would have been better had it abstained, in general, from making special hypotheses, based on immediate observations, and to limit oneself to the pure facts, i.e. to the results of measurements. However, the theory would thus surrender the most important aid, absolutely necessary to its development, namely, the setting up and consistent expansion

of ideas which lead to progress. For this, not only understanding, but also imagination is necessary. As it is, the mechanical theory of light has done its duty. Without it the present brilliant results of optics would not have been obtained so quickly.

Huygens's undulation theory has not been essentially altered by the electro-magnetic hypothesis, when it states that any disturbance spreads out from its source in concentric spherical waves. But it is electro-magnetic energy and not mechanical energy that is sent out, for an oscillating electric and magnetic field of force appears in place of periodic vibrations of the ether.

Considered from this advanced point of view, the study of light, or, as it is often more exactly called, the study of radiant energy, gives us a picture of a gigantic co-ordinated structure, unified and completed. In this, all electro-magnetic oscillations, though apparently of very different kinds, find their proper positions, and all are governed by the same laws of propagation, following Huygens's wave theory. On the one hand, we have the Hertzian waves a kilometre long; on the other, the hard Gamma rays, with many milliards of waves to the centimetre. The human eye has no place in this, it appears merely as an accidental and, although very delicate, a very limited piece of apparatus, for it can only perceive rays within a small spectral range of hardly an octave. Instead of the eye, special pieces of apparatus have been devised for receiving and measuring the different wave-lengths of the remainder of the spectrum. Such instruments are the wave detector, thermocouple, bolometer, radiometer, photographic plate, and the ionic cell. Thus, in optics, the separation of the physical foundations from the sense-perceptions has been accomplished in exactly the same way as in mechanics, where the conception of force has long lost its connection with the idea of muscular strength.

If I had delivered my lecture twenty years ago, I could have stopped here, for no further fundamental discoveries had then been made, and the imposing picture described above would have been a good conclusion which would have made modern physics famous. But probably I should not then have delivered this lecture, fearing that I should be able to present to you too little that was new. To-day it has become quite otherwise, for, since that time, the picture has been essentially changed. The proud structure, which I have just described to you, has recently revealed certain fundamental weaknesses, and not a few physicists maintain that new foundations are required already. The electro-magnetic theory must always remain untouched, but Huygens's wave theory is seriously threatened, at least in one essential detail, due to the discovery of certain new facts. Instead of collecting as many as possible of the multifarious facts available, I shall simple examine one of them in detail.

When ultra-violet rays fall on a piece of metal in a vacuum, a large number of electrons are shot off from the metal at a high velocity, and since the magnitude of this velocity does not essentially depend on the state of the metal, certainly not on its temperature, it is concluded that the energy of the electrons is not derived from the metal, but from the light rays which fall on the metal. This would not be strange in itself; it would even be assumed that the electro-magnetic energy of light waves is transformed into the kinetic energy of electronic movements. An apparently insuperable difficulty from the view of Huygens's wave theory is the fact (which was discovered by Philipp Lenard and others), that the velocity of the electrons does not depend on the intensity of the beam, but only on the wave-length, i.e. on the colour of light used. The velocity increases as the wave-length diminishes. If the distance between the metal and the source of light is continuously increased, using, for example, an electric spark as the source of light, the electrons continue to be flung off with the same velocity, in spite of the weakening of the illumination; the only difference is that the number of electrons thrown off per second decreases with the intensity of the light.

The difficulty is to state whence the electron obtains its energy, when the distance of the source of light becomes ultimately so great that the intensity of the light almost vanishes, and yet the electrons show no sign of diminution in their velocity. This must evidently be a case of a kind of accumulation of light energy at the spot from which the electron is flung out—an accumulation which is quite contrary to the uniform spreading out in all directions of electro-magnetic energy

according to Huygens's wave theory. However, if it is assumed that the light source does not emit its rays uniformly but in impulses, something like an intermittent light, it follows that the energy of such a flash, spreading outwards in all directions in uniform waves, would finally be distributed over the surface of a sphere so large that the metal considered would receive but little of it. It is easy to calculate that under certain circumstances radiation extending for minutes, even hours, would be necessary for the liberation of one electron with the velocity corresponding to the colour of the light, while, in fact, no limiting condition can be determined, for the duration of radiation necessary to produce the effects; the action certainly takes place with great rapidity. Like ultra-violet rays, Röntgen rays and Gamma rays give us the same effect, though, owing to the very much shorter wave-lengths of these rays, the velocities of the liberated electrons are much greater.

The only possible explanation for these peculiar facts appears to be that the energy radiated from the source of light remains, not only for all time, but also throughout all space, concentrated in certain bundles, or, in other words, that light energy does not spread out quite uniformly in all directions, becoming continuously less intense, but always remains concentrated in certain definite quanta, depending *only on the colour*, and that these quanta move in all directions with the velocity of light. Such a light-quantum, striking the metal, communicates its energy to an electron, and the energy always remains the same, however great the distance from the source of light.

Here we have Newton's emanation theory resurrected in another and modified form. But interference, which was a bar to the further development of Newton's emanation theory, is also an enormous difficulty in the quantum theory of light, for it is difficult at present to see how two exactly similar light quanta, moving independently in space, and meeting on a common path, can neutralize each other, without violating the principle of energy.

From this state of affairs arose the pressing need of the radiation theory for an investigation to find some way out of this dilemma, difficult from all sides. A natural assumption to try is that the energy of the electrons driven off comes from the metal itself and not from the radiation, and, therefore, that the radiation acts merely as a liberator in the same manner that a small spark liberates any amount of energy in a powder cask. But the further assumption would be necessary that the amount of the energy freed depends solely on the manner in which it is freed. It is not difficult to point out somewhat analogous phenomena in other branches of physics. As an example, I will consider in greater detail a convenient illustration used by Max Born. Imagine a tall apple tree, all its branches weighed down with ripe fruit, all of the same size, but with stalks of different lengths; the apples are arranged so that those with short stalks are higher than those with long stalks. If an extremely weak, uniform wind blows through the branches, all the apples will oscillate slightly, without any one dropping, and the higher apples will oscillate more rapidly than the lower ones. If, now, the tree is shaken very gently with a definite rhythm, resonance will increase the oscillations of those apples whose period agrees with the period of the shaking, and a certain number of these will fall, the number increasing the longer and more forcibly the tree is shaken. These apples will reach the ground with a certain definite velocity determined only by their original height, i.e. by the lengths of their stalks; all the other apples remain on the tree.

It must be understood that this comparison, like every other, fails in many respects, since, in this illustration, the source of energy is not internal kinetic energy but gravitation. But the essential point is realized that the final velocity of the particles liberated depends solely on the period of the disturbance, while the intensity of the disturbance determines only the number of these particles.

Can one attribute, however, such a complicated structure and such a wealth of energy to a tiny piece of metal? This question is less awkward than would perhaps appear at first. For we have long known that the chemical atom is not by any means the simple invariable element of which all matter is constituted, but rather that every single atom, particularly one of a heavy metal, must be considered as a world in itself, and the farther

one penetrates, the richer and more varied the structure appears. The energy contained in every gramme of a substance, according to the theory of relativity, amounts to over 20 billion calories, quite independently of its temperature—more than sufficient to liberate countless electrons.

Whether this presentation gives a possible way of saving the compromised wave theory, or simply leads ultimately to a blind alley, can only be settled by following the methods of research already outlined and seeing where they end. At this stage we must make use of theory. We must first of all examine more closely each of the two opposing hypotheses, without considering whether or not we have confidence in either of them, and must work out the results and reduce them to a form suitable for experimental verification. For this purpose, in addition to a training in physics and the requisite mathematical ability, it is necessary to have a discriminating judgment of the measure of the reliability that can be placed on the accuracy of the measurements; for the effects sought for are mostly of the same order as the errors of observation. It is not possible to-day to predict with certainty when any definite solution to this problem will be obtained.

What I have tried to set before you here about the action of light, holds in an exactly similar manner with regard to the cause of light, that is, to the phenomena of generation of light rays. In this also we have new riddles, difficult to unravel, which are at variance with certain surprisingly deep glimpses recently obtained into the laws governing natural phenomena. The only thing that can be said with certainty, is that the quanta, already referred to, play a characteristic part in connection with the origin of light.

According to the bold hypothesis of the Danish physicist Niels Bohr, the consequences of which have been astonishingly multiplied recently, electrons oscillate in every atom of an illuminated gas. These electrons circle about the nucleus in a greater or smaller number and at different distances, in certain definite paths and obey the same laws as those governing the motions of the planets about the sun. But light, arising from these oscillations, is not sent out from the atom into surrounding space uninterruptedly and uniformly, as are the sound waves from the prongs of a vibrating tuning-fork. The emission of light always takes place abruptly, by impulses, for it is not determined by the regular oscillations of the electrons themselves but is only emitted when these electron oscillations receive a sudden change and a certain disruption in themselves; a kind of internal catastrophe, which throws the electrons out of their original paths into others more stable but associated with less energy. It is the surplus amount of energy liberated by the atom which travels out into space as a light quantum.

Indeed, the most remarkable thing about this phenomenon is that the period of the emitted light, and therefore its colour, does not, in general, agree with the period of oscillation of the electrons, either in their original or in their final paths. It is definitely determined by the amount of energy emitted, since the more rapid the oscillations, the greater is the light quantum. It follows that a short wave-length corresponds to a large amount of energy, considered as a light quantum. If, therefore, for example, much energy is emitted, we get ultra-violet or even Röntgen rays; if, however, but little energy is emitted, red or infra-red rays result. It is at present a complete mystery why the oscillations of light produced in this way are, with the utmost regularity, strictly monochromatic.

Indeed, we might be inclined to consider all these ideas as the play of a vivid but empty imagination. When, on the other hand, we consider that these hypotheses help us to elucidate the mysterious structure of the spectra of the different chemical elements and, in particular, the complicated laws governing the spectral lines, not only as a whole but, as Arnold Sommerfeld first showed, partly even in minute details, with an exactness equal to, and even surpassing, that of the most accurate measurements—when we consider this we must, for good or ill, make up our minds to assign a real existence to these light quanta, at least at the instant of their origin.

What becomes of them later as light disperses—whether the energy of a quantum remains concentrated as in Newton's emanation theory or whether, as in Huygens's wave theory, it spreads out in all directions and gets less dense indefinitely—is

another question of a very fundamental character, to which I have referred above.

So the present lecture on our knowledge of the physical nature of light ends, not in a proud proclamation, but in a modest question. In fact, this question, whether light rays themselves consist of quanta, or whether the quanta exist only in matter, is the chief and most difficult dilemma before which the whole quantum theory halts, and the answer to this question will be the first step towards further development.