Physics 1928

OWEN WILLANS RICHARDSON

<<for his work on the thermionic phenomenon and especially-for the discovery of the law named after him>>

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Presentation Speech by Professor C. W. Oseen, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

Among the great problems that scientists conducting research in electrotechnique are today trying to solve, is that of enabling two men to converse in whatever part of the world each may be. In 1928 things had reached the stage when we could begin to establish telephonic communication between Sweden and North America. On that occasion there was a telephone line of more than 22,000 kilometres in length between Stockholm and New York. From Stockholm, speech was transmitted via Berlin to England by means of a cable and overhead lines; from England by means of wireless to New York; then, via a cable and lines by land, over to Los Angeles and back to New York, and from there by means of a new line to Chicago, returning finally to New York. In spite of the great distance, the words could be heard distinctly and this is explained by the fact that there were no fewer than 166 amplifiers along the line. The principle of construction of an amplifier is very simple. A glowing filament sends out a stream of electrons. When the speech waves reach the amplifier, they oscillate in tune with the sound waves but are weakened. The speech waves are now made to put the stream of electrons in the same state of oscillation as they have themselves. So exactly does the stream of electrons adapt itself to the speech waves that the amplification could be repeated 166 times without the distinctness of speech being lost.

I should like to give another example of what has recently been attained in that department. On the 16th of February 1928, there was a conference between the American Institute of Electrical Engineers in New York and the Institution of Electrical Engineers in London. The various speeches could be heard in both places by means of loud-speakers.

Most people here present will certainly be able to call to mind those anxious days, when news of the missing Nobile expedition was awaited all over the world. Everyone will no doubt remember that the first word of the lost expedition was picked up by a wireless amateur. I think that on this occasion it was clear to many people that wireless is not only a means of diversion - and as such, one of the more prominent - but also one of the most valuable expedients in the struggle against that sort of Nature which is still unconquered.

Every owner of a valve receiving-set knows the importance of the valve in the apparatus - the valve, the essential part of which is the glowing filament.

At the Jubilee, held in the twenty-fifth year of the reign of King Oscar II, our medical men were enabled to take up the struggle against the tuberculosis, thanks to the Jubilee Fund. At the Jubilee held on Your Majesty's 70th birthday, the fight against cancer was taken up in the same manner. We all know that Röntgen rays are one of the keenest weapons employed in this struggle. But we know, too, that this weapon is double-edged. The rays cannot only do good but also do harm. All depends on the accurate regulation of their strength and intensity. Quite recently, a change has taken place in this department. Röntgen rays are obtained when rapidly moving electrons collide with a solid body. By using a glowing filament in order to produce the electron stream, the means of regulating accurately the strength and intensity of Röntgen rays has been obtained.

Behind the progress which has here been briefly pointed out, lies the work of many men. But we have seen that they all have one thing in common. A <<red thread>> connects them - the glowing filament.

As early as 1737, a French scientist, Du Fay by name, found out that air in proximity to a glowing body is a conductor of electricity. Valuable researches concerning the character of this conductivity was made by Elster and Geitel, two German scientists. Their investigations were continued by Mr. J. J. Thomson, the Grand Old Man of English Physics of today. By these researches they have found it probable that the conductivity of air in proximity to a glowing metal depends on electrons in the air, which have been made free in some way or another. So far had the researches advanced when Mr. O. W. Richardson appeared and devoted himself to it. He began by laying down a theory for the phenomenon. According to this theory the phenomenon is bound up with the electrical conductivity of metals. The latter depends on the fact that there are free electrons in a metal. At higher temperatures these cannot, according to Mr. Richardson, be retained by the body but they are emitted according to a fixed law. But a theory alone does not give any knowledge of reality. That can be obtained only by means of experimental research. So Mr. Richardson proceeded to do this. The point was to find out if the theory was really right. The strenuous work of twelve years was necessary to settle this question. So hard was the struggle that even so late as in the twelfth year, there was a time when it was uncertain whether Mr. Richardson's theory was not completely wrong, and if the origin of the phenomenon was not quite different, being, for instance, chemical reactions between the metal and impurities in it. But in the end, Mr. Richardson's theory proved to be correct in all essential points. The most important fact was that Mr. Richardson's opinion about the thermion-phenomenon with fixed laws was totally confirmed. Through this fact a solid basis was obtained for the practical application of the phenomenon. Mr. Richardson's work has been the starting-point and the prop of the technical activity which has led to the progress of which I have just spoken.

Professor Richardson. You are a happy man. You possess the very thing that gives life its chief value. You can devote yourself with all your strength to the activity that you love. We constantly see the results of this activity come to light. Besides this, you are fortunate enough to see the harvest ripen to the benefit of mankind in the fields you tilled in your youth. For one who is so rich it is but a little thing to receive the greatest prize which the Royal Academy of Sciences has at its disposal as a reward for a scientific discovery. I ask you, however, to receive from our King's hand the Nobel Prize for Physics for the year 1928.

Owen W. Richardson

Thermionic phenomena and the laws which govern them

Nobel Lecture, December 12, 1929

In its broadest aspect this subject may be summarized as the branch of Physics which deals with the effect of heat on the interaction between electricity and matter. It is not altogether new. Nearly 200 years ago it was known that air in the neighbourhood of hot bodies conducted electricity. In 1873 Guthrie showed that a red-hot iron ball in air could retain a negative but not a Positive charge. In a series of researches extending from 1882 to 1889, Elster and Geitel examined the charge collected on an insulated plate placed near various hot wires in diverse gases at different pressures. The observed effects were very specific and varied, but there emerged a general tendency for the plate to acquire a positive charge at low temperatures and high pressures, and a negative charge at high temperatures and low pressures. The matter became really interesting in 1899 when J. J. Thomson showed that the discharge from an incandescent carbon filament in a vacuum tube was carried by negative electrons. In 1900 McClelland showed that the currents from a negatively charged platinum wire were influenced very little, if at all, by changes in the nature and pressure of the surrounding gas, if the pressure were fairly low. These facts seemed to me to be highly significant, and I resolved to investigate the phenomenon thoroughly.

The view of these effects generally held at that time by people who had thought about them was that the electric discharges were carried by ions and electrons which were generated by the interaction of the neighbouring gas molecules with the hot body. It was left an open question as to whether this action was merely thermal, a matter of kinetic energy, or was chemical, or involved the intervention of radiation. The effects observed in the best vacua were attributed to the residual gas which could not be got rid of. This was, of course, easily possible. I felt, however, that it was very likely that interacting gases had little to do with the main phenomenon, but that the negatively charged electrons and, possibly, the positively charged ions too were coming from the heated solid. This would be reasonable from the point of view of the theories of metallic conduction which had been put forward between 1888 and 1900 by Thomson, Riecke, and Drude. I decided that the best way to make progress was to get rid of the complications due to the presence of gases and to find out what, if anything, happened when gas effects were excluded.

This was not so easy at the beginning of this century as it would be at the present time. Largely owing to the technical importance of the phenomena under consideration the art of evacuating gases has advanced enormously since then. In those days the gas had all to be got away by hand pumps. As the heating of the tube walls and other parts of the apparatus by the hot wire generates gas from them which continues almost indefinitely this is a most tedious operation. I have often heated a wire in a tube for weeks in succession in order to make sure that the currents observed were stable and not coming from residual gas. There was no ductile tungsten; the most refractory material readily available in a reasonably pure form was platinum. In 1901 I was able to show that each unit area of a platinum surface emitted a limited number of electrons. This number increased very rapidly with the temperature, so that the maximum current i at any absolute temperature T was governed by the law

$$i = AT^{\frac{1}{2}}e^{-w/kT} \qquad (1)$$

In this equation k is Boltzmann's constant, and A and w are specific constants of the material. This equation was completely accounted for by the simple hypothesis that the freely moving electrons in the interior of the hot conductor escaped when they reached the surface provided that the part of their energy which depended on the component of velocity normal to the surface was greater than the work function w. In 1903 I showed that the same conclusions could be drawn for sodium and more qualitatively for carbon. Further, that the differences of the work functions of different substances should be equal to their contact potential differences, and the experimental values for platinum and sodium verified this. The results also verified the conclusion that the work functions for different elements should be of the same order of magnitude as $\frac{1}{2}(e^2/d)$, where e is the electronic charge and d the radius of the atom, and also that it should vary roughly as the inverse cube root of the atomic volume. In the same year Wehnelt found that similar phenomena were exhibited by a large number of metallic oxides. The alkaline earths in particular had an exceptionally low work function and were in consequence very efficient emitters of electrons.

It is necessary to say a word or two in parenthesis about the positive ionization which is frequently observed. This is due to an emission of positive ions which arises in various ways. When any ordinary sample of a solid is first heated, it gives rise to a copious emission of positive ions which decays (and sometimes recovers) with time in a manner which resembles superficially that of radioactive substances. This effect is due to impurities. After this has been got rid of, there may be another more stable emission characteristic of the substance itself. There is a third type which is a direct result of interaction between the heated solid and the surrounding gas. I devoted a good deal of time between 1904 and 1912 to the investigation of these effects. The results were interesting, but there is not time to consider them in any detail. I will only mention that all three types of positive emission, when stable, were found to obey the same temperature law $AT^{\frac{1}{2}}e^{-b/T}$ as the electronic emission but, of course, with different constants A, b; that the carriers of the characteristic emissions were charged atoms of the metallic constituent; and that the carriers of the temporary effect were singly charged atoms of sodium or potassium, the latter usually predominating, which are present as contaminants.

The central idea which lies behind the theory summarized in Eq. (I) is that of an electron gas evaporating from the hot source. If this idea is correct, the thermionic currents should be able to flow against a small opposing electromotive force because the kinetic energy of the heat motion of the electron gas molecules, in other words the electrons, will carry some of them through it. Furthermore, we could at that time find out a great deal more about what the electrons in an electron gas were doing than we could about the molecules of an ordinary gas. Owing to the fact that they are electrically charged, their motion can be controlled by an external electric field. By measuring the electronic current which flows against various directly opposing fields it is possible to ascertain the proportion of the emitted electrons which have a value of the component of their velocity perpendicular to the emitting surface between any assigned limits. By making observations of the spreading of the electrons sideways under different small accelerating fields it is possible to deduce similar information about the components of velocity parallel to the surface. By experiments of this kind made in 1908-1909, partly with the help of F. C. Brown, I was able to show that the distribution of velocity among the emitted electrons was identical with the Maxwell distribution for a gas, of equal molecular weight to that of the electron, at the temperature of the metal. The identity was shown to hold for each velocity component.

Apart from its interest in connection with electrons, this was the first experimental demonstration of Maxwell's law for any gas, although the law was enunciated by Maxwell in 1859.

There were two other matters which required urgent investigation before the theory of electron emission could be regarded as securely founded. The first was this. If the electrons are really coming out of the hot body by virtue of their heat energy being able to overcome the work function *iv*, the hot body should be cooled by this process. It is like the cooling of water by evaporation. I published a calculation of the magnitude of this effect in 1903, but the first experimental investigation was made by Wehnelt and Jentzsch in 1909. They observed a cooling effect, but the magnitude did not agree with the theory. In 1913 H. L. Cooke and I devised an improved experimental method of attacking this question, redetermined this cooling effect, and showed that it agreed with the value of the work function deduced from the variation of the thermionic currents with the temperature. Our conclusions have since been confirmed by the very accurate experiments of Davisson and Germer made in 1922.

The other matter to which I referred is the converse of this. If a stream of electrons flows into a conductor from outside, there should be a development of heat which does not depend either on the temperature of these electrons or on the magnitude of the small potential differences used to drive them. H. L. Cooke and I devised and put into operation an apparatus for detecting and measuring this effect in 1910-1911. The results showed a satisfactory agreement with the value of the work function obtained by the other two methods.

Despite the steadily accumulating mass of evidence to the contrary, some of which I have briefly outlined, the view had been fairly commonly held up to about 1913 that thermionic emission was not a physical phenomenon but a secondary effect of some chemical reaction between the hot body and the surrounding gas. The advent of ductile tungsten enabled me, in 1913, to get very big currents under better vacuum conditions than had hitherto been possible and to show that the mass of the electrons emitted exceeded the mass of the chemicals which could possibly be consumed. This experiment, I think, ended that controversy so far as it could be regarded seriously.

There is a very close relationship between thermionic and photoelectric phenomena. The photoelectric threshold frequency, the least frequency v_0 which will eject an electron from a given substance, is connected with the thermionic work function w_0 by the simple relation

$$w^0 = h\nu^0$$

where h is Planck's constant. This was established by experiments made by K. T. Compton and myself in 1912. We know that any body in thermal equilibrium at any temperature T is surrounded by a bath of radiation in which the frequency distribution is given by Planck's formula. This formula puts no finite limit on the magnitude of the frequencies occurring; so that there will always be some frequencies present for which ν_o is greater than w_0/h. Such frequencies will eject electrons by photoelectric action; so that the temperature radiation alone will, by a kind of photoelectric effect integrated over the whole spectrum, give rise to an electronic emission which should increase with the temperature. In 1912 I showed that it followed from the principles of thermodynamics that this integrated photoelectric emission would follow Eq. (I) exactly with, possibly, a different value for the constant A. This conclusion was established by direct experiment later by W. Wilson, in 1917. Thermionic emission might thus well be an integrated photoelectric emission; only the absolute magnitude could decide. In 1912 there were no known data which would enable the magnitude of this integrated photoelectric effect to be ascertained, so, with the collaboration first of K. T. Compton and later of F. J. Rogers, I set about to determine the absolute values of the photoelectric yields of various substances as a function of frequency. With the help of these absolute values I was able in 1916 to calculate the electron emission from platinum at 2,000° K due to its complete black-body spectrum. The result showed that thermionic emission is at least 5,000 times, and almost certainly 100 million times, as large; so that thermionic emission cannot be merely an integrated photoelectric effect, although it has the same thermodynamic properties. A photochemical theory of chemical reactions based on considerations analogous to these has been put forward independently by Penrrin and seems to have met with very similar difficulties. If we have to make a decision now, the verdict must be, on the facts at present revealed, that the part of these effects which is of radiational origin is comparatively unimportant. I am not sure, however, that the end has been heard of this matter. I have a feeling that there is something coordinating these radiational and mechanical or chemical effects which at present is concealed from us.

I will now say a few words about the relation between thermionic phenomena and theories of metallic conduction. In so far as it can be regarded as a serious contribution to scientific knowledge, thermionics was born at the same time as the theories of metallic conduction associated with J. J. Thomson, Riecke, Drude, and Lorentz, and it grew up with them. The dominant feature of these theories is the assumption that the currents in metals are carried by electrons which are moving freely and which possess the same average amount of kinetic energy as that of the molecule of a monatomic gas at the same temperature. Since all the thermionic facts which I have outlined received a ready explanation on these theories, there came to be a presumption that they favoured them rather than others, such as that put forward by Lindemann, which supposed the electrons in metals to be normally at rest. The fact that the experiments confirmed the requirement of the former theories, that the emitted electrons should have a Maxwell distribution of kinetic energy, especially seems to have led to the spreading of this opinion. It is a requirement of classical dynamics that this distribution should hold for electrons in any part of a system in thermal equilibrium, and as it is found to be true for the external electrons, the only part of the system accessible to experimental investigation, there is a presumption that it will also be true of the internal electrons. But this presumption has no validity apart from classical dynamics. Except for the considerations dealt with in the next paragraph which were perhaps still somewhat uncertain, the ascertained facts of thermionic emission did not favour one type of theory of metallic conduction rather than another until 1922, when Davisson and Germer made a very accurate comparison of the experimental value of the work function deduced from the cooling effect with that deduced from the temperature emission formula, at different temperatures, using the same tungsten filament. An analysis of their results showed that the experimental evidence was definitely against the classical theory of metallic conductors and in favour of a type of theory which makes the kinetic energy of the internal electrons practically independent of the temperature.

In 1911 as a result of pursuing some difficulties in connection with the thermodynamic theory of electron emission I came to the conclusion that

$$i = AT^2 e^{-w/kT} \tag{2}$$

was a theoretically preferable form of the temperature emission equation to Eq. (1) with, of course, different values of the constants A and w from those used with (1). It is impossible to distinguish between these two equations by experimenting. The effect of the T^2 or $T^{1/2}$ term is so small compared with the exponential factor that a small change in A and w will entirely conceal it. In fact, at my instigation K. K. Smith in 1915 measured the emission from tungsten over such a wide range of temperature that the current changed by a factor of nearly 10^{12}, yet the results seemed to be equally well covered by either (1) or (2). It is, of course, very satisfactory to know that either formula will do this. There are not many physical laws which have been tested over so wide a range. The great advantage of Eq. (2) is that it makes A a universal constant; so that there is only one specific constant for each substance, namely *w*. The first time I mentioned explicitly that A was a universal constant was in 1915. Here I came to it as a result of a thermodynamic argument about electron emission. In 1914 I had already come to it by a different route. I had come to the conclusion that the classical statistics were not applicable to the electrons inside conductors. There was no means of ascertaining what the correct statistics were, so I endeavoured to avoid this difficulty by adopting some quantum ideas previously used by Keesom to calculate the specific heat of helium at low temperatures. In this way I determined the constant A as $0.547\ mk^2e/h^3$ (*m* and *e* being the mass and charge of the electron, k and h Boltzmann and Planck's constants). These calculations have since been improved upon by others, but there still seems to be some doubt about the pure number factor which I made out to be 0.547. The most probable value of it seems to be 4π. Amongst those whose writings have made important contributions to this question since 1915 are von Laue (1918), Tolman (1921), Dushman (1923), Roy (1926), Sommerfeld (1927), and R. H. Fowler (1928).

By 1924 it was easy to prove that all the existing theories of metallic conduction were wrong, but just where they went wrong it was impossible to say. None of them were able to unite in a straightforward and satisfactory way such diverse facts as the law of Wiedemann and Franz, the large number of free electrons and the mean free paths required by the optical properties of metals, their known crystal structures, their small specific heats, the variation of conductivity with temperature and the existence of supraconductivity, and the relation between the thermionic cooling effect and the temperature.

This great problem was solved by Sommerfeld in 1927. Following up the work of Pauli on the paramagnetism of the alkali metals, which had just appeared, he. showed that the electron gas in metals should not obey the classical statistics as in the older theories, such as that of Lorentz for example, but should obey the new statistics of Fermi and Dirac. This makes a profound change in the distribution of velocities among the electrons when their concentration is very great, as in the interior of a metal, but it makes little or no difference when the concentration is small, as in the external electron atmospheres. It thus allows us to retain the experimentally established Maxwell distribution for the external electrons. On this theory the energy of the internal electrons is the energy of their Schrödinger proper values. If the concentration of the electrons is large, as in a metal, it is fixed almost entirely by the density of the electrons and has little to do with their temperature. It is, in fact, a kind of zero-point energy. This feature immediately accounts for the very small contribution of the electrons to the specific heats of metals, which was so great a difficulty for the older theories. It appears also to be capable of accounting for the other serious difficulties.

There is one other feature of Sommerfeld's theory which I must mention as it affects the interpretation to be put on the thermionic work function w. Before the advent of this theory w was interpreted as the work required to remove a free electron at rest inside the metal to a point outside. According to Sommerfeld's theory w is equal to the difference between this work and the maximum energy of the internal electrons. The value of this is

$$\frac{h^2}{2m}\left(\frac{3n}{8\pi}\right)^{\frac{2}{3}}$$

if n is the number in unit volume. For most metallic conductors this quantity is equivalent to about 10 volts. As *w* is generally somewhere about 4 volts, this means that the difference between the electrostatic potential energy of a free electron inside and outside a metal is some 3 or 4 times as large as was formerly supposed. Direct experimental evidence that this is correct is furnished by the recent experiments of Davisson and Germer on the diffraction of electrons by nickel crystals.

We have seen that the classical theories of metallic conduction gave a pretty good account of those thermionic phenomena which I have so far referred to. The only clear exceptions which emerged were the magnitude of the work function in relation to temperature as deduced from the cooling effect and the calculation of the actual magnitude of the absolute constant A which enters into the $AT^{2e-w/kT}$ formula. As this contains Planck's constant h its elucidation necessarily involved some form of quantum theory. As a historical fact, however, it was chiefly on other difficulties with the properties of metals that the older theories wrecked themselves. I come now to some thermionic phenomena with which the older theories were not so successful.

It became apparent at a very early stage that the emission of electrons from conductors at a given temperature was very susceptible to the influence of foreign substances and particularly to gaseous contaminants. This was not surprising in itself, as the phenomenon is essentially a surface phenomenon but some of the observed effects were unexpected. In 1903 H. A. Wilson made the important observation that the emission from platinum could be enormously increased by the presence of small quantities of hydrogen. In 1908 he showed that in certain circumstances this emission was a function of the pressure of the hydrogen at a fixed temperature. If the pressure was kept fixed, the currents still followed the $AT^{2}e^{-b/T}$ formula, but with changed values of A and b. These parameters were now functions of the pressure of such a kind that they obeyed an equation

$$b = c \log A + d \tag{3}$$

where c and d are new constants independent of both pressure and temperature. In 1913 Langmuir observed that the emission from tungsten was affected by various gases, hydrogen having a particularly depressing effect on this substance, although the effect may in reality be caused by water vapour. In 1915 I pointed out that in all these cases of contamination the currents still obeyed the $AT^{2}e^{-b/T}$ formula, with changed values of the parameters, but that all the values, including those for the pure metals, satisfied Eq. (3) with the same constants c and d. In 1925 A. F. A. Young and I extended the list to include potassium contaminated in a large number of ways. The number of substances which subscribe to Eq. (3) has recently been added to very considerably by several American investigators. This effect is not small, it is large. The parameter A can change by a factor of 10^{12} as a result of contamination.

Since 1915 I have felt that this result must be important both on account of its generality and of its magnitude, but I have never been able to arrive at any satisfactory reason for it. It seems now that this is one of those phenomena which are only to be accounted for with the help of the new waves of L. de Broglie. The solution of the problem we owe to R. H. Fowler and Nordheim (1928). Their explanation is similar in principle to that by which Gamow and Gurney and Condon explain the disintegration of the radioactive nucleus. They take the conventional simplified picture of a metal as a sharply bounded region of low potential energy densely packed with electrons. But as de Broglie has shown us, an electron can be regarded as a train of waves, or a wave packet, having a wavelength equal to h divided by the momentum of the electron. If such a wave is incident on the surface of the metal, it may be either reflected or transmitted. Thus the problem of the emission of electrons by a conductor may be looked upon as the problem of the reflection of the corresponding de Broglie waves at the hill of potential gradient which exists at the boundary. If the height of this hill is *H*, then on my old theory none of the electrons reaching the boundary would escape if their normal component *N* of kinetic energy were less than *H*, whereas all would escape for which *N* exceeded *H*. In the wave reflection problem it is still true that there is total reflection for *N* less than *H*, but the sharp discontinuity at $N = H$ has disappeared. It is found that the proportion transmitted is a continuous function of *N* and *H*, whose value tends to unity as the difference between *N* and H increases. This, however, makes very little difference; and when the calculations are completely carried out, it is found that Eq. (2) is still valid with the magnitude of the universal constant A unaltered in any essential way.

This result, however, depends essentially on the assumption that the potential energy increases to a permanent maximum as the electron crosses the surface. No doubt this is the correct picture for a pure metal, but for a contaminated one we may expect something different. If the contaminant is a thin layer, it may be only a few molecules thick, of a more electropositive substance, we should expect the hill to rise to a maximum height, let us say H_1, and then fall to a permanently lower level at a height H_2. On the old ideas the condition for escape would be that N should exceed the maximum height *H*, but in the wave problem it is possible for some of the waves to penetrate the hump H_1-H_2 provided its thickness is not large compared with the wavelength. There is a well-established optical analogue of this in the failure of total reflection when the thickness of the reflecting medium becomes comparable with the wavelength of the light. When the transmission of the de Broglie waves is calculated for this more complicated potential distribution, it is found that the emission formula (2) still holds good, but with new constants A and b, which are connected together by a relation which is equivalent to (3). I am not claiming that all the facts-in this department of thermionics have been' completely coordinated by these theories of Fowler and Nordheim, but it is satisfactory that we have begun to understand something about this intractable subject.

I come now to a phenomenon which is not exactly thermionic, as it is independent oftemperature, but in some ways it is intimately related to thermionic effects. It has been suspected for a long time that electrons-could be pulled out of metals without the co-operation of gases by sufficiently strong electric fields. The effects seemed very erratic and difficult to investigate. The reality of the phenomenon has, however, been firmly established by the work of Gossling, of Millikan and Eyring, and of Rother, during or a little prior to 1926, and by that of various experimenters since then. These currents are carried by electrons and they may be quite large. The magnitude is independent of the temperature of the emitting substance, but at the same time is a continuous function of the applied electric field. The theory of this effect was discussed at length by Schottky in 1923 and more briefly, but in relation to the new experimental data, by Millikan and Eyring in 1926. It does not seem to have been realized, however, that no rational treatment of the old particle theories would get the electrons out in a way which made the emission a continuous function of the field without at the same time being a function which was sensitive to the temperature. I noticed this important point in 1927, and accordingly I attacked the problem from a new point of view by regarding it as a Schrödinger wave problem of an electron in the field of force at the conducting surface. Perhaps the last word has not been said on this matter, but it now looks as though in this attempt I attributed too much importance to the mirror-image attraction of the electron in the surface. Whatever its ultimate importance may be, this paper first drew attention to essential physical aspects of this phenomenon and indicated in a general way the nature of its connection with thermionic effects. In 1928 the problem was attacked by Oppenheimer and, more completely, by Fowler and Nordheim, who succeeded in putting it into an exceedingly simple form. They treat it in the same way as they treated the problem of thermionic emission, namely as a problem in the reflection of de Broglie waves at a potential barrier. The only essential difference between the two problems is that the potential, instead of being constant outside the metal, now falls off as a linear function of the distance from the surface. Their solution of this problem leads to a formula which so far as I am able to judge, is in excellent agreement with the ascertained facts in this domain.

The existence of this-field extraction phenomenon has a number of interesting consequences, one of which I will now mention. If we consider an evacuated enclosure containing a number of bodies having different thermionic work functions w_1, w_2, etc., they will not be in electrical equilibrium unless their surfaces are charged. The reason for this is that those with lower work functions would emit electrons at a more rapid rate than those with higher work functions. The condition for equilibrium to a first approximation, and one which covers the essential features of the phenomenon, is that there should be a certain field of electric force between the different bodies. This is such that, if the potential difference between any point just outside the body with suffix I and any point just outside the body with suffix 2 is V_{12}, then $eV_{12} = w_1 - w_2$. V_{12} is the contact potential difference between the bodies I and 2. There is nothing essential to the thermionic argument which depends on the shape, size or relative position of the bodies, and the result should be the same whether they are interconnected by other conductors or insulated from each other. The quantities such as V_{12} are thus intrinsic potential differences which are characteristic properties of the materials of which the conductors are made.

The field extraction phenomenon requires a modification of this conclusion. To simplify the argument I consider only two bodies, those with suffixes 1 and 2. Some portion of each of them is bounded by a plane surface, and the bodies are arranged so that these plane surfaces are parallel to one another and a distance *x* apart. The more distant parts of the bodies may be united by an electric circuit which includes a galvanometer. When x is considerable, there is equilibrium and no current passes through the galvanometer, because the excess electrons emitted by the more electropositive body are kept back by the potential difference V_{12} and this equilibrium is practically unaffected by the small force eV_{12}/x. But now suppose x to become very small, let us say comparable with atomic dimensions. The force eV_{12}/x now becomes large and will begin to extract electrons from the more electronegative body. This upsets the equilibrium, which is restored by a current passing through the galvanometer. But this is a perpetuum mobile: the current can be made to do useful work. It consumes nothing and the apparatus has no moving parts. If it is argued that it may be tapping some source of heat, at least it must be a perpetuum mobile of the second kind, since it works at a constant temperature. What is the answer to this riddle? I say it is this: the contact potential difference V_{12} is not completely independent of the distance between the two bodies. When this distance becomes small, V_{12} diminishes, and this diminution takes place in such a way that the additional electron current from the more electropositive body which reaches the more electronegative body owing to the reduced value of V_{12} is just equal to the electron current which is extracted from the more electronegative body by the field. In particular when the bodies are in contact, V_{12} falls to zero or at any rate to a quantity of the order of the thermoelectric magnitudes. Well, this seems to correspond to the actual properties of the contact difference of potential, and I think it clears up an old difficulty in connection with it.

Biography

Owen Willans Richardson was born on the 26th of April, 1879, at Dewsbury, Yorkshire, England, as the only son of Joshua Henry and Charlotte Maria Richardson.

Educated at Batley Grammar School, he proceeded to Cambridge in 1897, having obtained an Entrance Major Scholarship at Trinity College; he gained First Class Honours in Natural Science at the examinations of the Universities of Cambridge and London, with particular distinctions in Physics and Chemistry. After graduating at Cambridge in 1900, he began to investigate the emission of electricity from hot bodies at the Cavendish Laboratory. In 1902 he was elected a Fellow of Trinity College, Cambridge. The law for the discovery of which the Nobel Prize was specially given, was first announced by him in a paper read before the Cambridge Philosophical Society on the 25th November, 1901, in the following words, as recorded in the published Proceedings: <<If then the negative radiation is due to the corpuscles coming out of the metal, the saturation current *s* should obey the law $s = AT^{½}e^{-b/T}$. This law is fully confirmed by the experiments to be described.>> Richardson continued working at this subject at Cambridge until 1906, when he was appointed Professor of Physics at Princeton University in America, where he remained until the end of 1913, working at thermionic emission, photoelectric action, and the gyromagnetic effect. In 1911 he was elected a member of the American Philosophical Society, and in 1913 a Fellow of the Royal Society, whereupon (1914) he returned to England as Wheatstone Professor of Physics at King's College in the University of London. Among his publications were: The Electron Theory of Matter, 1914 (2nd ed., 1916), *The Emission of Electricity from Hot Bodies*, 1916 (and ed., 1921), Molecular Hydrogen and its Spectrum, 1934.

He was awarded the Hughes Medal by the Royal Society (1920), especially for work on thermionics; elected President, Section A, of the British Association (1921) and President of the Physical Society, London (1926-1928); appointed Yarrow Research Professor of the Royal Society, London *1924-1944),* and knighted in 1939. Since 1914 he worked at thermionics, photoelectric effects, magnetism, the emission of electrons by chemical action, the theory of electrons, the quantum theory, the spectrum of molecular hydrogen, soft X-rays, the fine structure of Hα and D α. His last paper, with E. W. Foster, appeared in 1953. He received honorary degrees from the Universities of St. Andrews, Leeds, and London.

In 1906 he married Lillian Maud Wilson, the only sister of the well-known physicist H. A. Wilson, who was a fellow-student with him in Cambridge. There were two sons and one daughter of this marriage. After the death of his wife in 1945, Richardson married the physicist Henriette Rupp in 1948; he himself died in 1959.

Physics I929

Prince LOUIS-VICTOR DE BROGLIE

<<for his discovery of the wave nature of electrons>>

Physics 1929

Presentation Speech by Professor C. W. Oseen, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The question as to the nature of light rays is one of the oldest problems in physics. In the works of the ancient philosopers are to be found an indication and a rough outline of two radically different concepts of this phenomenon. However, in a clear and definite form they appear at the time when the foundations of physics were laid, a time that bears the stamp of Newton's genius. One of these theories asserts that a light ray is composed of small particles, which we may term corpuscles, which are projected into space by light-emitting substances. The other states that light is a wave motion of one type or another. The fact that these two theories, at this elementary stage, are equally possible, is attributable to their explaining equally well the simplest law governing a light ray, viz. conditions being undisturbed it propagates in a straight line.

The 19th century sealed the victory of the wave theory. Those of us whose studies coincide with that period have certainly all learned that light is a wave motion. This conviction was based on the study of a series of phenomena which are readily accounted for by the wave theory but which, on the other hand, cannot be explained by the corpuscular theory. One of these phenomena is the diffraction undergone by a light beam when it passes through a small hole in an opaque screen. Alongside the diffracted ray there are alternate light and dark bands. This phenomenon has long been considered a decisive proof of the wave theory. Furthermore, in the course of the 19th century a very large number of other, more complex, light phenomena had been learnt of which all, without exception, were completely explainable by the wave theory, while it appeared to be impossible to account for them on the basis of the corpuscular theory. The correctness of the wave theory seemed definitely established.

The 19th century was also the period when atomic concepts have taken root into physics. One of the greatest discoveries of the final decades of that century was the discovery of the electron, the smallest negative charge of electricity occurring in the free state.

Under the influence of these two currents of ideas the concept which 19th century physics had of the universe was the following. The universe was divided into two smaller worlds. One was the world of light, of waves; the other was the world of matter, of atoms and electrons. The perceptible appearance of the universe was conditioned by the interaction of these two worlds.

Our century taught us that besides the innumerable light phenomena which testify to the truth of the wave theory, there are others which testify no less decisively to the correctness of the corpuscular theory. A light ray has the property of liberating a stream of electrons from a substance. The number of electrons liberated depends on the intensity of the ray. But the velocity with which the electrons leave the substance is the same whether the light ray originates from the most powerful light source that can be made, or whether it originates from the most distant fixed stars which are invisible to the naked eye. In this case everything occurs as if the light ray were composed of corpuscles which traversed the spaces of the universe unmodified. It thus seems that light is at once a wave motion and a stream of corpuscles. Some of its properties are explained by the former supposition, others by the second. Both must be true.

Louis de Broglie had the boldness to maintain that not all the properties of matter can be explained by the theory that it consists of corpuscles. Apart from the numberless phenomena which can be accounted for by this theory, there are others, according to him, which can be explained only by assuming that matter is, by its nature, a wave motion. At a time when no single known fact supported this theory, Louis de Broglie asserted that a stream of electrons which passed through a very small hole in an opaque screen must exhibit the same phenomena as a light ray under the same conditions. It was not quite in this way that Louis de Broglie's experimental investigation concerning his theory took place. Instead, the phenomena arising when beams of electrons are reflected by crystalline surfaces, or when they penetrate thin sheets, etc. were turned to account. The experimental results obtained by these various methods have fully substantiated Louis de Broglie's theory. It is thus a fact that matter has properties which can be interpreted only by assuming that matter is of a wave nature. An aspect of the nature of matter which is completely new and previously quite unsuspected has thus been revealed to us.

Hence there are not two worlds, one of light and waves, one of matter and corpuscles. There is only a single universe. Some of its properties can be accounted for by the wave theory, others by the corpuscular theory.

In conclusion I would like to point out that what applies to matter applies also to ourselves since, from a certain point of view, we are part of matter.

A well-known Swedish poem has as its opening words <<My life is a wave>>. The poet could also have expressed his thought by the words: <<I am a wave>>. Had he done so, his words would have contained a premonition of man's present deepest understanding of the nature of matter.

Monsieur Louis de Broglie. When quite young you threw yourself into the controversy raging round the most profound problem in physics. You had the boldness to assert, without the support of any known fact, that matter had not only a corpuscular nature, but also a wave nature. Experiment came later and established the correctness of your view. You have covered in fresh glory a name already crowned for centuries with honour. The Royal Academy of Sciences has sought to reward your discovery with the highest recompense of which it is capable. I would ask you to receive from the hands of our King the Nobel Physics Prize for 1929.

LOUIS DE BROGLIE

The wave nature of the electron

Nobel Lecture, December 12, 1929

When in 1920 I resumed my studies of theoretical physics which had long been interrupted by circumstances beyond my control, I was far from the idea that my studies would bring me several years later to receive such a high and envied prize as that awarded by the Swedish Academy of Sciences each year to a scientist: the Nobel Prize for Physics. What at that time drew me towards theoretical physics was not the hope that such a high distinction would ever crown my work; I was attracted to theoretical physics by the mystery enshrouding the structure of matter and the structure of radiations, a mystery which deepened as the strange quantum concept introduced by Planck in 1900 in his research on black-body radiation continued to encroach on the whole domain of physics.

To assist you to understand how my studies developed, I must first depict for you the crisis which physics had then been passing through for some twenty years.

For a long time physicists had been wondering whether light was composed of small, rapidly moving corpuscles. This idea was put forward by the phi-osophers of antiquity and upheld by Newton in the 18th century. After Thomas Young's discovery of interference phenomena and following the admirable work of Augustin Fresnel, the hypothesis of a granular structure of light was entirely abandoned and the wave theory unanimously adopted. Thus the physicists of last century spurned absolutely the idea of an atomic structure of light. Although rejected by optics, the atomic theories began making great headway not only in chemistry, where they provided a simple interpretation of the laws of definite proportions, but also in the physics of matter where they made possible an interpretation of a large number of properties of solids, liquids, and gases. In particular they were instrumental in the elaboration of that admirable kinetic theory of gases which, generalized under the name of statistical mechanics, enables a clear meaning to be given to the abstract concepts of thermodynamics. Experiment also yielded decisive proof in favour of an atomic constitution of electricity; the concept of the electricity corpuscle owes its appearance to Sir J. J. Thomson and you will all be familiar with H. A. Lorentz's use of it in his theory of electrons.

Some thirty years ago, physics was hence divided into two: firstly the physics of matter based on the concept of corpuscles and atoms which were supposed to obey Newton's classical laws of mechanics, and secondly radiation physics based on the concept of wave propagation in a hypothetical continuous medium, i.e. the light ether or electromagnetic ether. But these two 'physics could not remain alien one to the other; they had to be fused together by devising a theory to explain the energy exchanges between matter and radiation - and that is where the difficulties arose. While seeking to link these two physics together, imprecise and even inadmissible conclusions were in fact arrived at in respect of the energy equilibrium between matter and radiation in a thermally insulated medium: matter, it came to be said, must yield all its energy to the radiation and so tend of its own accord to absolute zero temperature! This absurd conclusion had at all costs to be avoided. By an intuition of his genius Planck realized the way of avoiding it: instead of assuming, in common with the classical wave theory, that a light source emits its radiation continuously, it had to be assumed on the contrary that it emits equal and finite quantities, quanta. The energy of each quantum has, moreover, a value proportional to the frequency v of the radiation. It is equal to $h\nu$, h being a universal constant since referred to as Planck's constant.

The success of Planck's ideas entailed serious consequences. If light is emitted as quanta, ought it not, once emitted, to have a granular structure? The existence of radiation quanta thus implies the corpuscular concept of light. On the other hand, as shown by Jeans and H. Poincaré, it is demonstrable that if the motion of the material particles in light sources obeyed the laws of classical mechanics it would be impossible to derive the exact law of black-body radiation, Planck's law. It must therefore be assumed that traditional dynamics, even as modified by Einstein's theory of relativity, is incapable of accounting for motion on a very small scale.

The existence of a granular structure of light and of other radiations was confirmed by the discovery of the photoelectric effect. If a beam of light or of X-rays falls on a piece of matter, the latter will emit rapidly moving electrons. The kinetic energy of these electrons increases linearly with the frequency of the incident radiation and is independent of its intensity. This phenomenon can be explained simply by assuming that the radiation is composed of quanta $h\nu$ capable of yielding all their energy to an electron of the irradiated body: one is thus led to the theory of light quanta proposed by Einstein in 1905 and which is, after all, a reversion to Newton's corpuscular theory, completed by the relation for the proportionality between the energy of the corpuscles and the frequency. A number of arguments were put forward by Einstein in support of his viewpoint and in 1922 the discovery by A. H. Compton of the X-ray scattering phenomenon which bears his name confirmed it. Nevertheless, it was still necessary to adopt the wave theory to account for interference and diffraction phenomena and no way whatsoever of reconciling the wave theory with the existence of light corpuscles could be visualized.

As stated, Planck's investigations cast doubts on the validity of very small scale mechanics. Let us consider a material point which describes a small trajectory which is closed or else turning back on itself. According to classical dynamics there are numberless motions of this type which are possible complying with the initial conditions, and the possible values for the energy of the moving body form a continuous sequence. On the other hand Planck was led to assume that only certain preferred motions, quantized motions, are possible or at least stable, since energy can only assume values forming a discontinuous sequence. This concept seemed rather strange at first but its value had to be recognized because it was this concept which brought Planck to the correct law of black-body radiation and because it then proved its fruitfulness in many other fields. Lastly, it was on the concept of atomic motion quantization that Bohr based his famous theory of the atom; it is so familiar to scientists that I shall not summarize it here.

The necessity of assuming for light two contradictory theories-that of waves and that of corpuscles- and the inability to understand why, among the infinity of motions which an electron ought to be able to have in the atom according to classical concepts, only certain ones were possible: such were the enigmas confronting physicists at the time I resumed my studies of theoretical physics.

When I started to ponder these difficulties two things struck me in the main. Firstly the light-quantum theory cannot be regarded as satisfactory since it defines the energy of a light corpuscle by the relation $W = h\nu$ which contains a frequency ν. Now a purely corpuscular theory does not contain any element permitting the definition of a frequency. This reason alone renders it necessary in the case of light to introduce simultaneously the corpuscle concept and the concept of periodicity.

On the other hand the determination of the stable motions of the electrons in the atom involves whole numbers, and so far the only phenomena in which whole numbers were involved in physics were those of interference and of eigenvibrations. That suggested the idea to me that electrons themselves could not be represented as simple corpuscles either, but that a periodicity had also to be assigned to them too.

I thus arrived at the following overall concept which guided my studies: for both matter and radiations, light in particular, it is necessary to introduce the corpuscle concept and the wave concept at the same time. In other words the existence of corpuscles accompanied by waves has to be assumed in all cases. However, since corpuscles and waves cannot be independent because, according to Bohr's expression, they constitute two complementary forces of reality, it must be possible to establish a certain parallelism between the motion of a corpuscle and the propagation of the associated wave. The first objective to achieve had, therefore, to be to establish this correspondence.

With that in view I started by considering the simplest case: that of an isolated corpuscle, i.e. a corpuscle free from all outside influence. We wish to associate a wave with it. Let us consider first of all a reference system $Ox_0y_0z_0$ in which the corpuscle is immobile: this is the <<intrinsic>> system of the corpuscle in the sense of the relativity theory. In this system the wave will be stationary since the corpuscle is immobile: its phase will be the same at every point; it will be represented by an expression of the form sin $2\pi\nu_0(t_0-\tau_0)$; t_0 being the intrinsic time of the corpuscle and τ_0 a constant.

In accordance with the principle of inertia in every Galilean system, the corpuscle will have a rectilinear and uniform motion. Let us consider such a Galilean system and let $v = \beta c$ be the velocity of the corpuscle in this system; we shall not restrict generality by taking the direction of the motion as the x-axis. In compliance with Lorentz' transformation, the time t used by an observer of this new system will be associated with the intrinsic time t_0 by the relation:

$$t_0 = \frac{t - \frac{\beta x}{c}}{\sqrt{1-\beta^2}}$$

and hence for this observer the phase of the wave will be given by

$$\sin 2\pi \frac{\nu_0}{\sqrt{1-\beta^2}}\left(t - \frac{\beta x}{c} - \tau_0\right).$$

For him the wave will thus have a frequency:

$$\nu = \frac{\nu_0}{\sqrt{1 - \beta^2}}$$

and will propagate in the direction of the x-axis at the phase velocity:

$$V = \frac{c}{\beta} = \frac{c^2}{v}$$

By the elimination of b between the two preceding formulae the following relation can readily be derived which defines the refractive index of the vacuum *n* for the waves considered:

$$n = \sqrt{1 - \frac{\nu_0^2}{\nu^2}}$$

A <<group velocity>> corresponds to this <<law of dispersion>>. You will be aware that the group velocity is the velocity of the resultant amplitude of a group of waves of very close frequencies. Lord Rayleigh showed that this velocity *U* satisfies equation :

$$\frac{1}{U} = \frac{\partial (n\nu)}{\partial \nu}$$

Here U = v, that is to say that the group velocity of the waves in the system *xyxt* is equal to the velocity of the corpuscle in this system. This relation is of very great importance for the development of the theory.

The corpuscle is thus defined in the system *xyzt* by the frequency v and the phase velocity *V* of its associated wave. To establish the parallelism of which we have spoken, we must seek to link these parameters to the mechanical parameters, energy and quantity of motion. Since the proportionality between energy and frequency is one of the most characteristic relations of the quantum theory, and since, moreover, the frequency and the energy transform in the same way when the Galilean reference system is changed, we may simply write

energy = *h* x frequency, or $W = hv$

where h is Planck's constant. This relation must apply in all Galilean systems and in the intrinsic system of the corpuscle where the energy of the corpuscle, according to Einstein, reduces to its internal energy m_oc^2 (m_0 being the rest mass) we have

$$hvo = m_oc_2$$

This relation defines the frequency v_o as a function of the rest mass m_o, or inversely.

The quantity of movement is a vector; equal to

$$\frac{m_0 v}{\sqrt{1-\beta^2}}$$

and we have:

$$(p) = \frac{m_0 v}{\sqrt{1-\beta^2}} = \frac{Wv}{c^2} = \frac{h\nu}{V} = \frac{h}{\lambda}$$

The quantity; λ is the distance between two consecutive peaks of the wave, i.e. the <<wavelength>>. Hence:

$$\lambda = \frac{h}{p}$$

This is a fundamental relation of the theory.

The whole of the foregoing relates to the very simple case where there is no field of force at all acting on the corpuscles. I shall show you very briefly how to generalize the theory in the case of a corpuscle moving in a constant field of force deriving from a potential function *F(xyz)*. By reasoning which I shall pass over, we are then led to assume that the propagation of the wave corresponds to a refractive index which varies from point to point in space in accordance with the formula:

$$n(xyz) = \sqrt{\left[1 - \frac{F(xyz)}{h\nu}\right]^2 - \frac{\nu_0^2}{\nu^2}}$$

or to a first approximation if the corrections introduced by the theory of relativity are negligible

$$n(xyz) = \sqrt{\frac{2(E-F)}{m_0c^2}}$$

with $E = W - m_0c^2$. The constant energy W of the corpuscle is still associated with the constant frequency ν of the wave by the relation

$$W = h\nu$$

while the wavelength λ which varies from one point to another of the force field is associated with the equally variable quantity of motion p by the following relation

$$\lambda(xyz) = \frac{h}{p(xyz)}$$

Here again it is demonstrated that the group velocity of the waves is equal to the velocity of the corpuscle. The parallelism thus established between the corpuscle and its wave enables us to identify Fermat's principle for the waves and the principle of least action for the corpuscles (constant fields). Fermat's principle states that the ray in the optical sense which passes through two points A and B in a medium having an index *n(xyz)* varying from one point to another but constant in time is such that the integral $\int_A^B n\,dl$ taken along this ray is extreme. On the other hand Maupertuis' principle of least action teaches us the following: the trajectory of a corpuscle passing through two points A and B in space is such that the integral $\int_A^B p\,dl$ taken along the trajectory is extreme, provided, of course, that only the motions corresponding to a given energy value are considered. From the relations derived above between the mechanical and the wave parameters, we have:

$$n = \frac{c}{V} = \frac{c}{\nu} \cdot \frac{1}{\lambda} = \frac{c}{h\nu} \cdot \frac{h}{\lambda} = \frac{c}{W} p = \text{const.}\, p$$

since W is constant in a constant field. It follows that Fermat's and Maupertuis' principles are each a translation of the other and the possible trajectories of the corpuscle are identical to the possible rays of its wave.

These concepts lead to an interpretation of the conditions of stability introduced by the quantum theory. Actually, if we consider a closed trajectory C in a constant field, it is very natural to assume that the phase of the associated wave must be a uniform function along this trajectory. Hence we may write :

$$\int_C \frac{\mathrm{d}l}{\lambda} = \int_C \frac{1}{h}\, p\,\mathrm{d}l = \text{integer}$$

This is precisely Planck's condition of stability for periodic atomic motions. The conditions of quantum stability thus emerge as analogous to resonance phenomena and the appearance of integers becomes as natural here as in the theory of vibrating cords and plates.

The general formulae which establish the parallelism between waves and corpuscles may be applied to corpuscles of light on the assumption that here the rest mass m_0 is infinitely small. Actually, if for a given value of the energy W, m_0 is made to tend towards zero, v and V are both found to tend towards c and at the limit the two fundamental formulae are obtained on which Einstein had based his light-quantum theory

$$W = h\nu \qquad p = \frac{h\nu}{c}$$

Such are the main ideas which I developed in my initial studies. They showed clearly that it was possible to establish a correspondence between waves and corpuscles such that the laws of mechanics correspond to the laws of geometrical optics. In the wave theory, however, as you will know, geometrical optics is only an approximation: this approximation has its limits of validity and particularly when interference and diffraction phenomena are involved, it is quite inadequate. This prompted the thought that classical mechanics is also only an approximation relative to a vaster wave mechanics. I stated as much almost at the outset of my studies, i.e. << A new mechanics must be developed which is to classical mechanics what wave optics is to geometrical optics >>. This new mechanics has since been developed, thanks mainly to the fine work done by Schrödinger. It is based on wave propagation equations and strictly defines the evolution in time of the wave associated with a corpuscle. It has in particular succeeded in giving a new and more satisfactory form to the quantization conditions of intra-atomic motion since the classical quantization conditions are justified, as we have seen, by the application of geometrical optics to the waves associated with the intra-atomic corpuscles, and this application is not strictly justified.

I cannot attempt even briefly to sum up here the development of the new mechanics. I merely wish to say that on examination it proved to be identical with a mechanics independently developed, first by Heisenberg, then by Born, Jordan, Pauli, Dirac, etc. : quantum mechanics. The two mechanics, wave and quantum, are equivalent from the mathematical point of view.

We shall content ourselves here by considering the general significance of the results obtained. To sum up the meaning of wave mechanics it can be stated that: <<A wave must be associated with each corpuscle and only the study of the wave's propagation will yield information to us on the successive positions of the corpuscle in space>>. In conventional large-scale mechanical phenomena the anticipated positions lie along a curve which is the trajectory in the conventional meaning of the word. But what happens if the wave does not propagate according to the laws of optical geometry, if, say, there are interferences and diffraction? Then it is no longer possible to assign to the corpuscle a motion complying with classical dynamics, that much is certain. Is it even still possible to assume that at each moment the corpuscle occupies a well-defined position in the wave and that the wave in its propagation carries the corpuscle along in the same way as a wave would carry along a cork? These are difficult questions and to discuss them would take us too far and even to the confines of philosophy. All that I shall say about them here is that nowadays the tendency in general is to assume that it is not constantly possible to assign to the corpuscle a well-defined position in the wave. I must restrict myself to the assertion that when an observation is carried out enabling the localization of the corpuscle, the observer is invariably induced to assign to the corpuscle a position in the interior of the wave and the probability of it being at a particular point M of the wave is proportional to the square of the amplitude, that is to say the intensity at M.

This may be expressed in the following manner. If we consider a cloud of corpuscles associated with the same wave, the intensity of the wave at each point is proportional to the cloud density at that point (i.e. to the number of corpuscles per unit volume around that point). This hypothesis is necessary to explain how, in the case of light interferences, the light energy is concentrated at the points where the wave intensity is maximum: if in fact it is assumed that the light energy is carried by light corpuscles, photons, then the photon density in the wave must be proportional to the intensity.

This rule in itselfwill enable us to understand how it was possible to verify the wave theory of the electron by experiment.

Let us in fact imagine an indefinite cloud of electrons all moving at the same velocity in the same direction. In conformity with the fundamental ideas of wave mechanics we must associate with this cloud an indefinite plane wave of the form

$$a \sin 2\pi \left[\frac{W}{h} t - \frac{\alpha x + \beta y + \gamma z}{\lambda}\right]$$

where $\alpha\beta\gamma$ are the cosines governing the propagation direction and where the wavelength λ is equal to h/p. With electrons which are not extremely fast, we may write

$$p = m_0 v$$

and hence

$$\lambda = \frac{h}{m_0 v}$$

where m_0 *is the* rest mass of the electron.

You will be aware that in practice, to obtain electrons moving at the same velocity, they are made to undergo a drop in potential P and we have

$$\tfrac{1}{2} m_0 v^2 = eP$$

Hence,

$$\lambda = \frac{h}{\sqrt{2 m_0 e P}}$$

Numerically this gives

$$\lambda = \frac{12.24}{\sqrt{P}} \, 10^{-8} \text{ cm} \quad (P \text{ in volts})$$

Since it is scarcely possible to use electrons other than such that have undergone a voltage drop of at least some tens of volts, you will see that the wavelength λ predicted by theory is at most of the order of 10^{-8} cm, i.e. of the order of the Ångström unit. It is also the order of magnitude of X-ray wavelengths.

Since the wavelength of the electron waves is of the order of that of X-rays, it must be expected that crystals can cause diffraction of these waves completely analogous to the Laue phenomenon. Allow me to refresh your memories what is the Laue phenomenon. A natural crystal such as rock salt, for example, contains nodes composed of the atoms of the substances making up the crystal and which are regularly spaced at distances of the order of an Ångström. These nodes act as diffusion centres for the waves and if the crystal is impinged upon by a wave, the wavelength of which is also of the order of an Ångström, the waves diffracted by the various nodes are in phase agreement in certain well-defined directions and in these directions the total diffracted intensity is a pronounced maximum. The arrangement of these diffraction maxima is given by the nowadays well-known mathematical theory developed by von Laue and Bragg which defines the position of the maxima as a function of the spacing of the nodes in the crystal and of the wavelength of the incident wave. For X-rays this theory has been admirably confirmed by von Laue, Friedrich, and Knipping and thereafter the diffraction of X-rays in crystals has become a commonplace experience. The accurate measurement of X-ray wavelengths is based on this diffraction: is there any need to remind this in the country where Siegbahn and co-workers are continuing their fine work?

For X-rays the phenomenon of diffraction by crystals was a natural consequence of the idea that X-rays are waves analogous to light and differ from it only by having a smaller wavelength. For electrons nothing similar could be foreseen as long as the electron was regarded as a simple small corpuscle. However, if the electron is assumed to be associated with a wave and the density of an electron cloud is measured by the intensity of the associated wave, then a phenomenon analogous to the Laue phenomenon ought to be expected for electrons. The electron wave will actually be diffracted intensely in the directions which can be calculated by means of the Laue-Bragg theory from the wavelength $\lambda = h/mv$, which corresponds to the known velocity v of the electrons impinging on the crystal. Since, according to our general principle, the intensity of the diffracted wave is a measure of the density of the cloud of diffracted electrons, we must expect to find a great many diffracted electrons in the directions of the maxima. If the phenomenon actually exists it should thus provide decisive experimental proof in favour of the existence of a wave associated with the electron with wavelength h/mv, and so the fundamental idea of wave mechanics will rest on firm experimental foundations.

Now, experiment which is the final judge of theories, has shown that the phenomenon of electron diffraction by crystals actually exists and that it obeys exactly and quantitatively the laws of wave mechanics. To Davisson and Germer, working at the Bell Laboratories in New York, falls the honour of being the first to observe the phenomenon by a method analogous to that of von Laue for X-rays. By duplicating the same experiments but replacing the single crystal by a crystalline powder in conformity with the method introduced for X-rays by Debye and Scherrer, Professor G. P. Thomson of Aberdeen, son of the famous Cambridge physicist Sir J. J. Thomson, found the same phenomena. Then Rupp in Germany, Kikuchi in Japan, Ponte in France and others reproduced them, varying the experimental conditions. Today, the existence of the phenomenon is beyond doubt and the slight difficulties of interpretation posed by the first experiments of Davisson and Germer appear to have been satisfactorily solved.

Rupp has even managed to bring about electron diffraction in a particularly striking form. You will be familiar with what are termed diffraction gratings in optics: these are glass or metal surfaces, plane or slightly curved, on which have been mechanically traced equidistant lines, the spacing between which is comparable in order of magnitude with the wavelengths of light waves. The waves diffracted by these lines interfere, and the interferences give rise to maxima of diffracted light in certain directions depending on the interline spacing, on the direction of the light impinging on the grating, and on the wavelength of this light. For a long time it proved impossible to achieve similar phenomena with this type of man-made diffraction grating using X-rays instead of light. The reason was that the wavelength of X-rays is much smaller than that of light and no instrument can draw lines on a surface, the spacing between which is of the order of magnitude of X-ray wavelengths. A number of ingenious physicists (Compton, J. Thibaud) found how to overcome the difficulty. Let us take an ordinary optical diffraction grating and observe it almost tangentially to its surface. The lines of the grating will appear to us much closer together than they actually are. For X-rays impinging at this almost skimming incidence on the grating the effect will be as if the lines were very closely set and diffraction phenomena analogous to those of light will occur. This is what the above-mentioned physicists confirmed. But then, since the electron wavelengths are of the order of X-ray wavelengths, it must also be possible to obtain diffraction phenomena by directing a beam of electrons on to an optical diffraction grating at a very low angle. Rupp succeeded in doing so and was thus able to measure the wavelength of electron waves by comparing them directly with the spacing of the mechanically traced lines on the grating.

Thus to describe the properties of matter as well as those of light, waves and corpuscles have to be referred to at one and the same time. The electron can no longer be conceived as a single, small granule of electricity; it must be associated with a wave and this wave is no myth; its wavelength can be measured and its interferences predicted. It has thus been possible to predict a whole group of phenomena without their actually having been discovered. And it is on this concept of the duality of waves and corpuscles in Nature, expressed in a more or less abstract form, that the whole recent development of theoretical physics has been founded and that all future development of this science will apparently have to be founded.

Biography

Prince Louis-Victor de Broglie of the French Academy, Permanent Secretary of the Academy of Sciences, and Professor at the Faculty of Sciences at Paris University, was born at Dieppe (Seine Infiérieure) on 15th August, 1892, the son of Victor, Due de Broglie and Pauline d'Armaillé. After studying at the Lycée Janson of Sailly, he passed his school-leaving certificate in 1909. He applied himself first to literary studies and took his degree in history in 1910. Then, as his liking for science prevailed, he studied for a science degree, which he gained in 1913. He was then conscripted for military service and posted to the wireless section of the army, where he remained for the whole of the war of 1914-1918. During this period he was stationed at the Eiffel Tower, where he devoted his spare time to the study of technical problems. At the end of the war Louis de Broglie resumed his studies of general physics. While taking an interest in the experimental work carried out by his elder brother, Maurice, and co-workers, he specialized in theoretical physics and, in particular, in the study ofproblems involving quanta. In 1924 at the Faculty of Sciences at Paris University he delivered a thesis *Recherches sur la Théorie des Quanta* (Researches on the quantum theory), which gained him his doctor's degree. This thesis contained a series of important findings which he had obtained in the course of about two years. The ideas set out in that work, which first gave rise to astonishment owing to their novelty, were subsequently fully confirmed by the discovery of electron diffraction by crystals in 1927 by Davisson and Germer; they served as the basis for developing the general theory nowadays known by the name of *wave mechanics,* a theory which has utterly transformed our knowledge of physical phenomena on the atomic scale.

After the maintaining of his thesis and while continuing to publish original work on the new mechanics, Louis de Broglie took up teaching duties. On completion of two year's free lectures at the Sorbonne he was appointed to teach theoretical physics at the Institut Henri Poincart which had just been built in Paris. The purpose of that Institute is to teach and develop mathematical and theoretical physics. The incumbent of the chair of theoretical physics at the Faculty of Sciences at the University of Paris since 1932, Louis de Broglie runs a course on a different subject each year at the Institut Henri Poincaré, and several of these courses have been published. Many French and foreign students have come to work with him and a great deal of doctorate theses have been prepared under his guidance.

Between 1930 and 1950, Louis de Broglie's work has been chiefly devoted to the study of the various extensions of wave mechanics: Dirac's electron theory, the new theory of light, the general theory of spin particles, applications of wave mechanics to nuclear physics, etc. He has published numerous notes and several papers on this subject, and is the author of more than twenty-five books on the fields of his particular interests.

Since 1951, together with young colleagues, Louis de Broglie has resumed the study of an attempt which he made in 1927 under the name of the theory of the double solution to give a causal interpretation to wave mechanics in the classical terms of space and time, an attempt which he had then abandoned in the face of the almost universal adherance of physicists to the purely probabilistic interpretation of Born, Bohr, and Heisenberg. Back again in this his former field of research, he has obtained a certain number of new and encouraging results which he has published in notes to *Comptes Rendus* de *l'Académie des Sciences* and in various expositions.

After crowning Louis de Broglie's work on two occasions, the Académie des Sciences awarded him in 1929 the Henri Poincaré medal (awarded for the first time), then in 1932, the Albert I of Monaco prize. In 1929 the Swedish Academy of Sciences conferred on him the Nobel Prize for Physics <<for his discovery of the wave nature of electrons>>. In 1952 the first Kalinga Prize was awarded to him by UNESCO for his efforts to explain aspects of modern physics to the layman. In 1956 he received the gold medal of the French National Scientific Research Centre. He has made major contributions to the fostering of international scientific co-operation.

Elected a member of the Academy of Sciences of the French Institute in 1933, Louis de Broglie has been its Permanent Secretary for the mathematical sciences since 1942. He has been a member of the Bureau des Longitudes since 1944. He holds the Grand Cross of the Legion d'Honneur and is an Officer of the Order of Leopold of Belgium. He is an honorary doctor of the Universities of Warsaw, Bucharest, Athens, Lausanne, Quebec, and Brussels, and a member of eighteen foreign academies in Europe, India, and the U.S.A.

Professor de Broglie’s most important publications are:

Recherches sur la théorie des quanta (Researches on the quantum theory), Thesis Paris, 1924.

Ondes et mouvements (Waves and motions), Gauthier-Villars, Paris, 1926.

Rapport au *5e Conseil de Physique Solvay,* Brussels, 1927.

La mécanique ondulatoire (Wave mechanics), Gauthier-Villars, Paris, 1928.

Une tentative d’interprétation causale et non linéaire de la mécanique ondulatoire: la théorie de la double solution, Gauthier-Villars, Paris, 1956.

English translation: *Non-linear Wave Mechanics:* A *Causal Interpretation,* Elsevier, Amsterdam, 1960.

Introduction à la nouvelle théorie des particules de M.Jean-Pierre Vigier et de *ses collaborateurs,* Gauthier-Villars, Paris, 1961.

English translation: *Introduction to the Vigier Theory of Elementary Particles,* Elsevier, Amsterdam, 1963.

Étude critique des bases de l’interprétation actuelle de la mécanique ondulatoire, Gauthier-Villars, Paris, 1963.

English translation: *The Current Interpretation of Wave Mechanics: A Critical Study,* Elsevier, Amsterdam, 1964.

Physics 1930

Sir CHANDRASEKHARA

VENKATA RAMAN

<<for his work on the scattering of light and for the discovery of the effect named after him>>

Physics 1930

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Academy of Sciences, has resolved to award the Nobel Prize in Physics for 1930 to Sir Venkata Raman for his work on the scattering of light and for the discovery of the effect named after him.

The diffusion of light is an optical phenomenon, which has been known for a long time. A ray of light is not perceptible unless it strikes the eye directly. If, however, a bundle of rays of light traverses a medium in which extremely fine dust is present, the ray of light will scatter to the sides and the path of the ray through the medium will be discernible from the side. We can represent the course of events in this way; the small particles of dust begin to oscillate owing to electric influence from the ray of light, and they form centres from which light is disseminated in all directions. The wavelength, or the number of oscillations per second, in the light thus diffused is here the same as in the original ray of light. But this effect has different degrees of strength for light with different wavelengths. It is stronger for the short wavelengths than for the long ones, and consequently it is stronger for the blue part of the spectrum than for the red part. Hence if a ray of light containing all the colours of the spectrum passes through a medium, the yellow and the red rays will pass through the medium without appreciable scattering, whereas the blue rays will be scattered to the sides. This effect has received the name of the <<Tyndall effect>>.

Lord Rayleigh, who has made a study of this effect, has put forward the hypothesis that the blue colours of the sky and the reddish colouring that is observed at sunrise and sunset is caused by the diffusion of light owing to the fine dust or the particles of water in the atmosphere. The blue light from the sky would thus be light-scattered to the sides, while the reddish light would be light that passes through the lower layers of the atmosphere and which has become impoverished in blue rays owing to scattering. Later, in 1899, Rayleigh threw out the suggestion that the phenomenon in question might be due to the fact that the molecules of air themselves exercised a scattering effect on the rays of light.

In 1914 Cabannes succeeded in showing experimentally that pure and dustless gases also have the capacity of scattering rays of light.

But a closer examination of scattering in different substances in solid, liquid, or gaseous form showed that the scattered light did not in certain respects exactly follow the laws which, according to calculation, should hold good for the Tyndall effect. The hypothesis which formed the basis of this effect would seem to involve, amongst other things, that the rays scattered to the sides were polarized. This, however, did not prove to be exactly the case.

This divergence from what was to be expected was made the starting-point of a searching study of the nature of scattered light, in which study Raman was one of those who took an active part. Raman sought to find the explanation of the anomalies in asymmetry observed in the molecules. During these studies of his in the phenomenon of scattering, Raman made, in 1928, the unexpected and highly surprising discovery that the scattered light showed not only the radiation that derived from the primary light but also a radiation that contained other wavelengths, which were foreign to the primary light.

In order to study more closely the properties of the new rays, the primary light that was emitted from a powerful mercury lamp was filtered in such a way as to yield a primary light of one single wavelength. The light scattered from that ray in a medium was watched in a spectrograph, in which every wavelength or frequency produces a line. Here he found that, in addition to the mercury line chosen, there was obtained a spectrum of new sharp lines, which appeared in the spectrograph on either side of the original line. When another mercury line was employed, the same extra spectrum showed itself round it. Thus, when the primary light was moved, the new spectrum followed, in such a way that the frequency distance between the primary line and the new lines always remained the same.

Raman investigated the universal character of the phenomenon by using a large number of substances as a scattering medium, and everywhere found the same effect.

The explanation of this phenomenon, which has received the name of the <<Raman effect>> after its discoverer, has been found by Raman himself, with the help of the modern conception of the nature of light. According to that conception, light cannot be emitted from or absorbed by material otherwise than in the form of definite amounts of energy or what are known as <<light quanta>>. Thus the energy of light would possess a kind of atomic character. A quantum of light is proportionate to the frequency of rays of light, so that in the case of a frequency twice as great, the quanta of the rays of light will also be twice as great.

In order to illustrate the conditions when an atom emits or absorbs light energy, we can, according to Bohr, picture to ourselves the atom as consisting of a nucleus, charged with positive electricity round which negative electrons rotate in circular paths at various distances from the centre. The path of every such electron possesses a certain energy, which is different for different distances from the central body.

Only certain paths are stable. When the electron moves in such a path, no energy is emitted. When, on the other hand, an electron falls from a path with higher energy to one with lower energy - that is to say, from an outer path to an inner path - light is emitted with a frequency that is characteristic of these two paths, and the energy of radiation consists of a quantum of light. Thus the atom can give rise to as many frequencies as the number of different transitions between the stable paths. There is a line in the spectrum corresponding to each frequency.

An incoming radiation cannot be absorbed by the atom unless its light quantum is identical with one of the light quanta that the atom can emit.

Now the Raman effect seems to conflict with this law. The positions of the Raman-lines in the spectrum do not correspond, in point of fact, with the frequencies of the atom itself, and they move with the activating ray. Raman has explained this apparent contradiction and the coming into existence of the lines by the effect of combination between the quantum of light coming from without and the quanta of light that are released or bound in the atom. If the atom, at the same time as it receives from without a quantum of light, emits a quantum of light of a different magnitude, and if the difference between these two quanta is identical with the quantum of light which is bound or released when an electron passes from one path to another, the quantum of light coming from without is absorbed. In that case the atom will emit an extra frequency, which either will be the sum of or the difference between the activating ray and a frequency in the atom itself. In this case these new lines group themselves round the incoming primary frequency on either side of it, and the distance between the activating frequency and the nearest Raman-lines will be identical with the lowest oscillation frequencies of the atom or with its ultrared spectrum.What has been said as to the atom and its oscillations also holds good of the molecule.

In this way we get the ultrared spectrum moved up to the spectral line of the activating light. The discovery of the Raman-line has proved to be of extraordinarily great importance for our knowledge of the structure of molecules.

So far, indeed, there have been all but insuperable difficulties in the way of studying these ultrared oscillations, because that part of the spectrum lies so far away from the region where the photographic plate is sensitive. Raman's discovery has now overcome these difficulties, and the way has been opened for the investigation of the oscillations of the nucleus of the molecules. We choose the primary ray within that range of frequency where the photographic plate is sensitive. The ultrared spectrum, in the form of the Raman-lines, is moved up to that region and, in consequence of that, exact measurements of its lines can be effected.

In the same way the ultraviolet spectrum can be investigated with the help of the Raman effect. Thus we have obtained a simple and exact method for the investigation of the entire sphere of oscillation of the molecules.

Raman himself and his fellow-workers have, during the years that have elapsed since the discovery was made, investigated the frequencies in a large number of substances in a solid, liquid, and gaseous state. Investigations have been made as to whether different conditions of aggregation affect atoms and molecules, and the molecular conditions in electrolytic dissociation and the ultrared absorption spectrum of crystals have been studied.

Thus the Raman effect has already yielded important results concerning the chemical constitution of substances; and it is to foresee that the extremely valuable tool that the Raman effect has placed in our hands will in the immediate future bring with it a deepening of our knowledge of the structure of matter.

Sir Venkata Raman. The Royal Academy of Sciences has awarded you the Nobel Prize in Physics for your eminent researches on the diffusion of gases and for your discovery of the effect that bears your name. The Raman effect has opened new routes to our knowledge of the structure of matter and has already given most important results.

I now ask you to receive the prize from the hands of His Majesty.

SIR CHANDRASEKHARA V. RAMAN

The molecular scattering of light

Nobel Lecture, December 11, 1930

The colour of the sea

In the history of science, we often find that the study of some natural phenomenon has been the starting-point in the development of a new branch of knowledge. We have an instance of this in the colour of skylight, which has inspired numerous optical investigations, and the explanation of which, proposed by the late Lord Rayleigh, and subsequently verified by observation, forms the beginning of our knowledge of the subject of this lecture. Even more striking, though not so familiar to all, is the colour exhibited by oceanic waters. A voyage to Europe in the summer of 1921 gave me the first opportunity of observing the wonderful blue opalescence of the Mediterranean Sea. It seemed not unlikely that the phenomenon owed its origin to the scattering of sunlight by the molecules of the water. To test this explanation, it appeared desirable to ascertain the laws governing the diffusion of light in liquids, and experiments with this object were started immediately on my return to Calcutta in September, 1921. It soon became evident, however, that the subject possessed a significance extending far beyond the special purpose for which the work was undertaken, and that it offered unlimited scope for research. It seemed indeed that the study of light-scattering might carry one into the deepest problems of physics and chemistry, and it was this belief which led to the subject becoming the main theme of our activities at Calcutta from that time onwards.

The theory of fluctuations

From the work of the first few months, it became clear that the molecular scattering of light was a very general phenomenon which could be studied not only in gases and vapours but also in liquids and in crystalline and amorphous solids, and that it was primarily an effect arising from molecular disarray in the medium and consequent local fluctuations in its optical density. Except in amorphous solids, such molecular disarray could presumably be ascribed to thermal agitation, and the experimental results appeared to support this view. The fact that molecules are optically anisotropic and can orientate freely in liquids was found to give rise to an additional type of scattering. This could be distinguished from the scattering due to fluctuations in density by reason of its being practically unpolarized, whereas the latter was completely polarized in the transverse direction. The whole subject was critically reviewed and the results till then obtained were set out in an essay published by the Calcutta University Press in February 1922.

The various problems requiring solution indicated in this essay were investigated with the aid of a succession of able collaborators. It is possible to mention briefly only a few of the numerous investigations which were carried out at Calcutta during the six years 1922 to 1927. The scattering of light in fluids was studied by Ramanathan over a wide range of pressures and temperatures with results which appeared to support the <<fluctuation>> theory of its origin. His work also disclosed the remarkable changes in the state of polarization which accompany the variations of intensity with temperature in vapours and in liquids. Liquid mixtures were investigated by Kameswara Rao, and furnished optical proof of the existence in such systems, of simultaneous fluctuations of density, composition, and molecular orientation. Srivastava studied the scattering of light in crystals in relation to the thermal fluctuations of density and their increase with temperature. Ramdas investigated the scattering of light by liquid surfaces due to thermal agitation, and established a relation between surface-tension and surface-opalescence. He also traced the transition from surface-opalescence to volume-opalescence which occurs at the critical temperature. Sogani investigated X-ray diffraction in liquids, in order to connect it with their optical behaviour, and test the application of fluctuation theory to X-ray scattering.

The anisotropy of molecules

As stated above, the state of polarization of the light scattered in fluids is connected with the optical anisotropy of the molecules. Much of the work done at Calcutta during the years 1922 to 1927 was intended to obtain data concerning this property and to establish its relations with various optical phenomena. Krishnan examined a great many liquids, and by his work showed very clearly the dependence of the optical anisotropy of the molecule on its chemical constitution. Ramakrishna Rao studied the depolarization of scattered light in a very large number of gases and vapours, and obtained information of high importance for the progress of the subject. Venkateswaran studied the scattering of light in aqueous solutions to find the influence on it of electrolytic dissociation. Ramachandra Rao investigated liquids having highly elongated molecules and also highly polar substances over a wide range of temperatures, and discovered the influence of molecular shape and molecular association on the depolarization of scattered light in liquids.

The interpretation of the observations with liquids involved the development of a molecular theory of light-scattering in dense media which was undertaken by Ramanathan, myself, and Krishnan. A revised opalescence formula was derived which differed from that of Einstein and yielded results in better agreement with observation. Krishnan and myself also published a series of investigations showing how the optical anisotropy of the molecules deduced from light-scattering could be utilized to interpret the optical and dielectric behaviour of fluids, and also the electric, magnetic, and mechanical birefringence exhibited by them. The conclusions derived from these studies enabled a connection to be established between the molecular anisotropy observed in fluids and the optical, electric, and magnetic aeolotropy exhibited by solids in the crystalline state.

A new phenomenon

The investigations referred to above were in the main guided by the classical electromagnetic theory of light, the application of which to the problems of light-scattering is chiefly associated with the names of Rayleigh and of Einstein. Nevertheless, the possibility that the corpuscular nature of light might come into evidence in scattering was not overlooked and was in fact elaborately discussed in the essay of February 1922 which was published at least a year before the well-known discoveries of Compton on X-ray scattering. While our experiments in the main appeared to support the electromagnetic theory of light, evidence came to hand at a very early stage of the investigations of the existence of a phenomenon which seemed to stand outside the classical scheme of thought. The scattering of light in transparent fluids is extremely feeble, much weaker in fact than the Tyndall effect usually observed in turbid media. It was experimentally discovered that associated with the Rayleigh-Einstein type of molecular scattering, was another and still feebler type of secondary radiation, the intensity of which was of the order of magnitude of a few hundredths of the classical scattering, and differed from it in not having the same wavelength as the primary or incident radiation. The first observation of this phenomenon was made at Calcutta in April 1923 by Ramanathan who was led to it in attempting to explain why in certain liquids (water, ether, methyl and ethyl alcohols), the depolarization of scattered light varied with the wavelength of the incident radiation. Ramanathan found that after exhaustive chemical purification and repeated slow distillation of the liquid in vacuum, the new radiation persisted undiminished in intensity, showing that it was a characteristic property of the substance studied and not due to any fluorescent impurity. Krishnan observed a similar effect in many other liquids in 1924, and a somewhat more conspicuous phenomenon was observed by me in ice and in optical glasses.

The optical analogue of the Compton effect

The origin of this puzzling phenomenon naturally interested us, and in the summer of 1925, Venkateswaran attempted to investigate it by photographing the spectrum of the scattered light from liquids, using sunlight filtered through colour screens, but was unable to report any decisive results. Ramakrishna Rao in his studies on the depolarization of scattering during 1926 and 1927 looked carefully for a similar phenomenon in gases and vapours, but without success. This problem was taken up again by Krishnan towards the end of 1927. While his work was in progress, the first indication of the true nature of the phenomenon came to hand from a different quarter. One of the problems interesting us at this time was the behaviour in light-scattering of highly viscous organic liquids which were capable of passing over into the glassy state. Venkateswaran undertook to study this question, and reported the highly interesting result that the colour of sunlight scattered in a highly purified sample of glycerine was a brilliant green instead of the usual blue. The phenomenon appeared to be similar to that discovered by Ramanathan in water and the alcohols, but of much greater intensity, and, therefore, more easily studied. No time was lost in following up the matter. Tests were made with a series of filters transmitting narrow regions of the solar spectrum and placed in the path of the incident beam, which showed that in every case the colour of the scattered light was different from that of the incident light, and was displaced from it towards the red. The radiations were also strongly polarized. These facts indicated a clear analogy between the empirical characters of the phenomenon and the Compton effect. The work of Compton had made familiar the idea that the wavelength of radiation could be degraded in the process of scattering, and the observations with glycerine suggested to me that the phenomenon which had puzzled us ever since 1923 was in fact the optical analogue of the Compton effect. This idea naturally stimulated further investigation with other substances.

The chief difficulty which had hitherto oppressed us in the study of the new phenomenon was its extreme feebleness in general. This was overcome by using a 7-inch refracting telescope in combination with a short-focus lens to condense sunlight into a pencil of very great intensity. With these arrangements and using complementary light-filters in the path of the incident and scattered beams, as was done by Ramanathan in 1923, to isolate the modified radiations, it was found that they could be readily observed in a great many liquids, and that in many cases they were strongly polarized. Krishnan, who very materially assisted me in these investigations, found at the same time that the phenomenon could be observed in several organic vapours, and even succeeded in visually determining the state of polarization of the modified radiations from them. Compressed gases such as CO, and N_2O, crystalline ice, and optical glasses also were found to exhibit the modified radiations. These observations left little doubt that the phenomenon was really a species of light-scattering analogous to the Compton effect.

The spectroscopic characters of the new effect

Thanks to the vastly more powerful illumination made available by the 7-inch refractor, the spectroscopic examination of the effect, which had been abandoned in 1925 as indecisive, now came within the reach of direct visual study. With a Zeiss cobalt-glass filter placed in the path of the incident beam and one or other of a series of organic liquids as the scattering substance, a band in the blue-green region was observed by me in the spectrum of the scattered light, separated by a dark interval from the indigo-violet region transmitted by the filter. *Both* of these regions in the spectrum became sharper when the region of transmission was narrowed by the insertion of an additional filter in the incident beam. This suggested the employment, instead of sunlight, of the highly monochromatic radiations given by a mercury arc in combination with a condenser of large aperture and a cobalt-glass filter.

With these arrangements the spectrum of the scattered light from a variety of liquids and solids was visually examined, and the startling observation was made that the spectrum generally included a number of sharp lines or bands on a diffuse background which were not present in the light of the mercury arc.

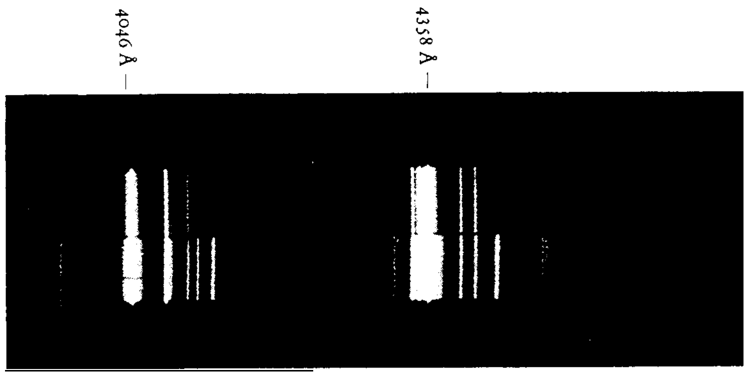

Fig. I. Spectrum of carbon tetrachloride.

The quartz mercury lamp was so powerful and convenient a source of monochromatic illumination that, at least in the case of liquids and solids, photographing the spectrum of scattered light was found to present no extraordinary difficulties. The earliest pictures of the phenomenon were in fact taken with a portable quartz spectrograph of the smallest size made by the firm of Hilger. With a somewhat larger instrument of the same type, Krishnan obtained very satisfactory spectrograms with liquids and with crystals on which measurements of the desired precision could be made, and on which the presence of lines displaced towards the violet was first definitely established. The experimental difficulties were naturally greater in the case of gases or vapours, though they could be lessened by working with the substance under pressure. With an improvised instrument of large aperture (F/1.8), Ramdas obtained the first spectrograms with a gaseous substance (ether vapour) at atmospheric pressure.

In interpreting the observed phenomena, the analogy with the Compton effect was adopted as the guiding principle. The work of Compton had gained general acceptance for the idea that the scattering of radiation is a unitary process in which the conservation principles hold good. Accepting this idea it follows at once that, if the scattering particle gains any energy during the encounter with the quantum, the latter is deprived of energy to the same extent, and accordingly appears after scattering as a radiation of diminished frequency. From thermodynamic principles, it follows that the reverse process should also be possible. Adopting these ideas, the actual observations could be interpreted, and the agreement of the observed displacements with the infrared frequencies of the molecules made it clear that the new method opened up an illimitable field of experimental research in the study of the structure of matter.

Interpretation of the effect

It appears desirable to emphasize that though the conservation principle of Compton is useful in interpreting the effects disclosed by experiment, it is by itself insufficient to explain the observed phenomena. As is well known from studies on molecular spectra, a gaseous molecule has four different species of energy of increasing orders of magnitude, namely those corresponding to translatory motion, rotation, vibration, and electronic excitation. Each of these, except the first, is quantized and may be represented by an integer in an extended sequence of quantum numbers. The aggregate energy of a molecule may, therefore, assume any one out of a very large number of possible values. If we assume that an exchange of energy occurs in the collision between the molecule and the quantum, and limit ourself to the cases in which the final energy of the molecule is less than that of the incident quantum, we arrive at the result that the spectrum of the scattered light should contain an immense number of new lines and should in fact rival in its complexity the band spectrum of the molecule observed in the emission or absorption of light. Nothing more different from what is actually observed can be imagined than the foregoing picture. The most conspicuous feature revealed by experiment is the beautiful simplicity of the spectra of even complicated polyatomic molecules obtained in light-scattering, a simplicity that is in striking contrast to the extreme complexity of their emission or absorption spectra. It is this simplicity that gives to the study of light-scattering its special significance and value. It is clear that the effect actually observed was not and could not have been foreseen from an application of the conservation principles.

The general principle of correspondence between the quantum and classical theories enunciated by Niels Bohr enables us, on the other hand, to obtain a real insight into the actual phenomena. The classical theory of light-scattering tells us that if a molecule scatters light while it is moving, rotating or vibrating, the scattered radiations may include certain frequencies, different from those of the incident waves. This classical picture, in many respects, is surprisingly like what we actually observe in the experiments. It explains why the frequency shifts observed fall into three classes, translational, rotational and vibrational, of different orders of magnitude. It explains the observed selection rules, as for instance, why the frequencies of vibration deduced from scattered light include only the fundamentals and not the overtones and combinations which are so conspicuous in emission and absorption spectra. The classical theory can even go further and give us a rough indication of the intensity and polarization of the radiations of altered frequency. Nevertheless, the classical picture has to be modified in essential respects to give even a qualitative description of the phenomena, and we have, therefore, to invoke the aid of quantum principles. The work of Kramers and Heisenberg, and the newer developments in quantum mechanics which have their root in Bohr's correspondence principle seem to offer a promising way of approach towards an understanding of the experimental results. But until we know much more than we do at present regarding the structure of molecules, and have sufficient quantitative experimental knowledge of the effect, it would be rash to suggest that they afford a complete explanation of it.

The significance of *the effect*

The universality of the phenomenon, the convenience of the experimental technique and the simplicity of the spectra obtained enable the effect to be used as an experimental aid to the solution of a wide range of problems in physics and chemistry. Indeed, it may be said that it is this fact which constitutes the principal significance of the effect. The frequency differences determined from the spectra, the width and character of the lines appearing in them, and the intensity and state of polarization of the scattered radiations enable us to obtain an insight into the ultimate structure of the scattering substance. As experimental research has shown, these features in the spectra are very definitely influenced by physical conditions, such as temperature and state of aggregation, by physico-chemical conditions, such as mixture, solution, molecular association and polymerization, and most essentially by chemical constitution. It follows that the new field of spectroscopy has practically unrestricted scope in the study of problems relating to the structure of matter. We may also hope that it will lead us to a fuller understanding of the nature of light, and of the interactions between matter and light.

Some concluding remarks

From a physical point of view, the quantitative study of the effect with the simplest molecules holds out the largest hope of fundamental advances. The beautiful work of McLennan with liquefied gases, and of R. W. Wood and Rasetti are pioneer investigations in this field which command the highest admiration. The quantitative study of the effect with crystals of the simplest possible chemical constitution is naturally of great importance. The case of the diamond, which has been investigated by Ramaswamy, Robertson, and Fox, and with especial completeness by Bhagavantam, is of special interest. Very surprising results have been obtained with this substance, which may be the pathway to a fuller understanding of the nature of the crystalline state. I should also like to draw attention to the work of Krishnamurti, who has traced a remarkable dependence of the intensity of the spectral lines observed in scattering on the nature of the chemical bond, and followed the transition from the homopolar to the heteropolar type of chemical combination. Krishnamurti's observation that the paramagnetism of crystals apparently influences the observed intensity of the displaced lines is one of the most remarkable ever made in this new field of research.

Biography

Chandrasekhara Venkata Raman was born at Trichinopoly in Southern India on November 7th, 1888. His father was a lecturer in mathematics and physics so that from the first he was immersed in an academic atmosphere. He entered Presidency College, Madras, in 1902, and in 1904 passed his B.A. examination, winning the first place and the gold medal in physics; in 1907 he gained his M.A. degree, obtaining the highest distinctions.

His earliest researches in optics and acoustics-the two fields of investigation to which he has dedicated his entire career-were carried out while he was a student.

Since at that time a scientific career did not appear to present the best possibilities, Raman joined the Indian Finance Department in 1907; though The duties of his office took most of his time, Raman found opportunities for carrying on experimental research in the laboratory of the Indian Association for the Cultivation of Science at Calcutta (of which he became Honorary Secretary in 1919).

In 1917 he was offered the newly endowed Palit Chair of Physics at Calcutta University, and decided to accept it. After 15 years at Calcutta he became Professor at the Indian Institute of Science at Bangalore (1933-1948), and since 1948 he is Director of the Raman Institute of Research at Bangalore, established and endowed by himself. He also founded the *Indian]ournal of Physics* in 1926, of which he is the Editor. Raman sponsored the establishment of the Indian Academy of Sciences and has served as President since its inception. He also initiated the *Proceedings* of that academy, in which much of his work has been published, and is President of the Current Science Association, Bangalore, which publishes *Current Science (India).*

Some of Raman’s early memoirs appeared as *Bulletins of the Indian Association for the Cultivation of Science* (Bull. 6 and 11, dealing with the <<Maintenance of Vibrations>>; Bull. 15,1918, dealing with the theory of the musical instruments of the violin family). He contributed an article on the theory of musical instruments to the 8th Volume of the *Handbuch der Physik,* 1928. In 1922 he published his work on the *Molecular Diffraction of Light>>, the first of a series of investigations with his collaborators which ultimately led to his discovery, on the 28th of February, 1928, of the radiation effect which bears his name (<<A new radiation>>, *Indian J. Phys.*, 2 (1928) 387), and which gained him the 1930 Nobel Prize in Physics.

Other investigations carried out by Raman were: his experimental and theoretical studies on the diffraction of light by acoustic waves of ultrasonic and hypersonic frequencies (published 1934-1942), and those on the effects produced by X-rays on infrared vibrations in crystals exposed to ordinary light. In 1948 Raman, through studying the spectroscopic behaviour of crystals, approached in a new manner fundamental problems of crystal dynamics. His laboratory has been dealing with the structure and properties of diamond, the structure and optical behaviour of numerous iridescent substances (labradorite, pearly felspar, agate, opal, and pearls).

Among his other interests have been the optics of colloids, electrical and magnetic anisotropy, and the physiology of human vision.

Raman has been honoured with a large number of honorary doctorates and memberships of scientific societies. He was elected a Fellow of the Royal Society early in his career (1924), and was knighted in 1929.

Physics 1931

Prize not awarded

Physics 1932 and 1933

WERNER HEISENBERG

[1934]

<<for *the creation of quantum mechanics, the application of which has, among other things, led to the discovery of the allotropic forms of hydrogen*>>

ERWIN SCHRÖDINGER

PAUL ADRIEN MAURICE DIRAC

[1933]

<<*for the discovery of new productive forms of atomic theory*>>

Physics 1932 and 1933

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

This year's Nobel Prizes for Physics are dedicated to the new atomic physics. The prizes, which the Academy of Sciences has at its disposal, have namely been awarded to those men, Heisenberg, Schrödinger, and Dirac, who have created and developed the basic ideas of modern atomic physics.

It was Planck who, in 1900, first expressed the thought that light had atomic properties, and the theory put forward by Planck was later more exhaustively developed by Einstein. The conviction, arrived at by different paths, was that matter could not create or absorb light, other than in quantities of energy which represented the multiple of a specific unit of energy. This unit of energy received the name of light quantum or photon. The magnitude of the photon is different for different colours of light, but if the quantity of energy of a photon is divided by the frequency of oscillation of the ray of light, the same number is always obtained, the so-called Planck's constant h. This constant is thus of a universal nature and forms one of the foundation stones for modem atomic physics.

Since light too was thus divided into atoms it appeared that all phenomena could be explained as interactions between atoms of various kinds. Mass was also attributed to the atom of light, and the effects which were observed when light rays were incident upon matter could be explained with the help of the law for the impact of bodies.

Not many years passed before the found connection between the photon and the light ray led to an analogous connection between the motion of matter and the propagation of waves being sought for.

For a long time it had been known that the customary description of the propagation of light in the form of rays of light, which are diffracted and reflected on transmission from one medium to another, was only an approximation to the true circumstances, which only held good so long as the wavelength of the light was infinitesimally small compared with the dimensions of the body through which the light passed, and of the instruments with which it was observed. In reality light is propagated in the form of waves which spread out in all directions according to the laws for the propagation of waves.

Prince Louis de Broglie conceived the brilliant idea of seeking an analogy between the path of the light ray and the track of a material point. He wondered whether the track of a particle of matter, like the path of a ray of light, might only be an approximate expression for reality, prescribed by the coarseness of our senses, and whether one here was not also dealing with wave motion. Using Einstein's theory of relativity, he was equally successful in representing the motion of matter as a combination of waves which were propagating themselves with velocities greater than that of light. Matter is formed or represented by a great number of this kind of waves which have somewhat different velocities of propagation and such phase that they combine at the point in question. Such a system of waves forms a crest which propagates itself with quite a different velocity from that of its component waves, this velocity being the so-called group velocity. Such a wave crest represents a material point which is thus either formed by it or connected with it, and is called a wave packet. De Broglie now found that the velocity of the material point was in fact the group velocity of the matter-wave.

De Broglie's theory of matter-waves subsequently received experimental confirmation. If a relatively slowly travelling electron meets a crystal surface, diffraction and reflection phenomena appear in the same way as if an incident beam of waves were concerned.

As a result of this theory one is forced to the conclusion to conceive of matter as not being durable, or that it can have definite extension in space. The waves, which form the matter, travel, in fact, with different velocity and must, therefore, sooner or later separate. Matter changes form and extent in space. The picture which has been created, of matter being composed of unchangeable particles, must be modified.

One of the physical phenomena whose correct explanation has proved most difficult, is the appearance of the spectra of countless lines land: bands which are obtained if light is split up by optical instruments when produced by atoms and molecules as a result of their vibrations. It has been known for a long time that each such line corresponds to light of a certain frequency, which varies according to where the line appears in the various parts of the colour spectrum.

A correct explanation of the intensities of all these lines and their positions in the spectrum is of fundamental significance since it gives us an insight into the structure of the atoms and molecules and the relationships within them.

It was Bohr who, in 1913, expressed the idea that Planck's constant should be taken as the determining factor for movements within the atom, as well as for the emission and absorption of light waves.

Bohr assumed, after Rutherford, that an atom consists of an inner, heavy, positively charged particle, around which negative, light electrons circulate in closed paths, held to the nucleus by the attraction. According to whether the path of the electron is further away, or closer from the nucleus, the electron possesses different velocity and different energy. Bohr now put forward the hypothesis that only such paths exist where the energy of the electron, as a result of its motion in the path, is a whole multiple of a quantum of light corresponding to the rotation frequency of the electron. Light, Bohr now assumed, appears if an electron suddenly transfers from one path to another, and the frequency of the light ray emitted, is obtained if the change of energy experienced during transfer is divided by Planck's constant. The frequencies which Bohr thus obtained held good for a hydrogen atom which has only one electron, but when his method was applied to more complicated atoms and to certain optical phenomena, theory and practice did not agree. The fact that Bohr's hypothesis met the case for the hydrogen atom, however, suggested that Planck's constant was, in one way or another, a determining factor for the light-vibrations of the atoms. On the other hand, one had the feeling that it could not be right to apply the laws of classical mechanics to the rapid movements in the atoms. Efforts made from various sides to develop and improve Bohr's theory proved also in vain. New ideas were required to solve the problem of oscillations of atoms and molecules.

This solution followed in 1925 upon the works of Heisenberg, Schrödinger, and Dirac in which different starting-points and methods were applied.

I will first of all dwell upon Schrödinger's contribution since it is more closely than the others connected to the state of the development which atomic physics had attained at that period of time, particularly as a result of de Broglie's above-mentioned theory of matter-waves.

Since the electrons were the seat of outgoing waves, Schrödinger thought that it should be possible to find a wave equation for the motions executed by the electrons which would define these waves in the same way as the wave equation which determined the propagation of light. From the solution of this wave equation one should be able to select those oscillations which were feasible for the motions within the atoms. He was successful, too, in determining the wave equation for a series of different motions of the electron. and it turned out that these equations gave finite solutions only when the energy of the system had specific discrete values, determined by Planck's constant. In Bohr's theory these discrete energy values of the electron paths were only hypothetical, but in Schrödinger's, on the contrary, they appeared as completely determined by the form of the wave equation. Schrödinger himself, and others after him, have applied his wave theory to various optical problems including the interpretation of the phenomena accompanying the impact between light rays and electrons, investigations into the behaviour of atoms in electric and magnetic fields, the diffraction of light rays, etc. In every direction, values and formulae have been obtained using Schrödinger's theory, which have been in closer agreement with experience than the older theories were. Schrödinger's wave equation has provided a convenient and simple method for handling problems to do with light spectra, and has become an indispensible tool for the present-day physicist.

Somewhat before the appearance of Schrödinger's theory Heisenberg brought out his famous quantum mechanics. Heisenberg started off from quite different standpoints and viewed his problem, from the very beginning, from so broad an angle that it took care of systems of electrons, atoms, and molecules. According to Heisenberg one must start from such physical quantities as permit of direct observation, and the task consists of finding the laws which link these quantities together. The quantities first of all to be considered are the frequencies and intensities of the lines in the spectra of atoms and molecules. Heisenberg now considered the combination of all the oscillations of such a spectrum as *one* system, for the mathematical handling of which, he set out certain symbolical rules of calculation. It had formerly been determined already that certain kinds of motions within the atom must be viewed as independent from one another to a certain degree, in the same way that a specific difference is made in classical mechanics between parallel motion and rotational motion. It should be mentioned in this connection that in order to explain the properties of a spectrum it had been necessary to assume self-rotation of the positive nuclei and the electrons. These different kinds of motion for atoms and molecules produce different systems in Heisenberg's quantum mechanics. As the fundamental factor of Heisenberg's theory can be put forward the rule set out by him with reference to the relationship between the position coordinate and the velocity of an electron, by which rule Planck's constant is introduced into the quantum-mechanics calculations as a determining factor.

Although Heisenberg's and Schrödinger's theories had different starting-points and were developed by the use of different processes of thought, they produced the same results for problems treated by both theories.

Heisenberg's quantum mechanics has been applied by himself and others to the study of the properties of the spectra of atoms and molecules, and has yielded results which agree with experimental research. It can be said that Heisenberg's quantum mechanics has made possible a systemization of spectra of atoms. It should also be mentioned that Heisenberg, when he applied his theory to molecules consisting of two similar atoms, found among other things that the hydrogen molecule must exist in two different forms which should appear in some given ratio to each other. This prediction of Heisenberg's was later also experimentally confirmed.

Dirac has set up a wave mechanics which starts from the most general conditions. From the start he put forward the requirement that the postulate of the relativity theory be fulfilled. Viewed from this general formulation of the problems it appeared that the self-rotation of the electron which had previously come into the theory as an hypothesis stipulated by experimental facts, now appeared as a result of the general theory of Dirac.

Dirac divided the initial wave equation into two simpler ones, each providing solutions independently. It now appeared that one of the solution systems required the existence of positive electrons having the same mass and charge as the known negative electrons. This initially posed considerable difficulty for Dirac's theory, since positively charged particles were known only in the form of the heavy atom nucleus. This difficulty which at first opposed the theory has now become a brilliant confirmation of its validity. For later on, positive electrons, the positrons, whose existence was stipulated in Dirac's theoretical investigation, have been found by experiment.

The new quantum mechanics has changed to a great extent all our concepts of the relationships existing within the microscopic world, made up of atoms and molecules. We have already mentioned that as a result of the new wave mechanics we have had to modify our conception on the unchangeability of material particles. But more than this. Heisenberg has shown that according to quantum mechanics it is inconceivable to determine, at a given instant of time, both the position taken up by a particle and its velocity. Closer study of quantum mechanics shows in fact that the more one attempts to fix exactly the position of a particle, the more uncertain the determination of its velocity becomes, and vice versa. It must be further considered, that it is impossible to carry out the measurement of the situation in an atom or molecule without the employed instruments, illumination, etc. themselves altering the situation which is under examination. The light emitted from the electrons becomes modified in the optical instruments. The relationships go still deeper however. As a result of the introduction of light quanta, quantum mechanics must abandon the requirement of causality within the microcosmic world. A ray of light on being incident upon an optical instrument is resolved. However, the photon is indivisible. It must be realized then, that some photons will behave in one way, others in another way at the resolution. The only assertion that can be made regarding causality is that the physical laws signify a certain probability that one or another incident will take place. Since we can only perceive average values because of the imperfection of our senses and instruments, it is probabilities which are covered in our physical laws, and the question has been raised, whether in the physical world there is in fact any other accordance with laws than a statistical one.

Professor Heisenberg. It has fallen to you whilst young in years, to have given to physics, by means of the theory of quantum mechanics established by you, a general method for the solution of the manifold problems which have come to the fore as a result of restless experimental researches into the theory of radiation. From a study of the properties of the molecules, you have succeeded, among other things, in predicting that the hydrogen molecules would appear in two forms, which later has been confirmed. Your quantum mechanics has created new concepts, and has led physics into fresh trains of thought, which have now already proved of fundamental importance for our knowledge of the phenomena of physics.

The Royal Academy of Sciences has awarded you the Nobel Prize for Physics for 1932 in recognition of these studies, and I beg you to accept this distinction from the hands of His Majesty the King.

Professor Schrödinger. Through a study of the wave properties of matter you have succeeded in establishing a new system of mechanics which also holds good for motion within the atoms and molecules. With the aid of this so-called wave mechanics you have found the solution to a number of problems in atomic physics. Your theory provides a simple and convenient method for the study of the properties of atoms and molecules under various external conditions and it has become a great aid to the development of physics.

For your discovery of new fruitful forms of atomic physics and the application of these, the Royal Academy of Sciences has decided to award you the Nobel Prize. I request you to receive this from the hands of His Majesty the King.

Professor Dirac. The theory of wave mechanics which you have developed is characterized by its universality, since from the beginning you have imposed the condition that the postulate of the theory of relativity has to be fulfilled. In this way you have shown that the existence of the spin of electrons and its qualities are a consequence of this theory and not merely a hypothesis.

Further you have succeeded in dividing the wave equation into two, which results in two systems of solutions one of which requires the existence of a positive electron of the same size and charge as the negative electron. The experimental discovery of the existence of the positron has in a brilliant way confirmed your theory.

For the discovery of new fertile forms of the theory of atoms presented by you and for its applications the Royal Academy of Sciences has awarded you the Nobel Prize, and I now ask you to receive this prize from the hands of His Majesty the King.

WERNER HEISENBERG

The development of quantum mechanics

Nobel Lecture, December 11, 1933

Quantum mechanics, on which I am to speak here, arose, in its formal content, from the endeavour to expand Bohr's principle of correspondence to a complete mathematical scheme by refining his assertions. The physically new viewpoints that distinguish quantum mechanics from classical physics were prepared by the researches ofvarious investigators engaged in analysing the difficulties posed in Bohr's theory of atomic structure and in the radiation theory of light.

In 1900, through studying the law of black-body radiation which he had discovered, Planck had detected in optical phenomena a discontinuous phenomenon totally unknown to classical physics which, a few years later, was most precisely expressed in Einstein's hypothesis of light quanta. The impossibility of harmonizing the Maxwellian theory with the pronouncedly visual concepts expressed in the hypothesis of light quanta subsequently compelled research workers to the conclusion that radiation phenomena can only be understood by largely renouncing their immediate visualization. The fact, already found by Planck and used by Einstein, Debye, and others, that the element of discontinuity detected in radiation phenomena also plays an important part in material processes, was expressed systematically in Bohr's basic postulates of the quantum theory which, together with the Bohr-Sommerfeld quantum conditions of atomic structure, led to a qualitative interpretation of the chemical and optical properties of atoms. The acceptance of these basic postulates of the quantum theory contrasted uncompromisingly with the application of classical mechanics to atomic systems, which, however, at least in its qualitative affirmations, appeared indispensable for understanding the properties of atoms. This circumstance was a fresh argument in support of the assumption that the natural phenomena in which Planck's constant plays an important part can be understood only by largely foregoing a visual description of them. Classical physics seemed the limiting case of visualization of a fundamentally unvisualizable microphysics, the more accurately realizable the more Planck's constant vanishes relative to the parameters of the system. This view of classical mechanics as a limiting case of quantum mechanics also gave rise to Bohr's principle of correspondence which, at least in qualitative terms, transferred a number of conclusions formulated in classical mechanics to quantum mechanics. In connection with the principle of correspondence there was also discussion whether the quantum-mechanical laws could in principle be of a statistical nature; the possibility became particularly apparent in Einstein's derivation of Planck's law of radiation. Finally, the analysis of the relation between radiation theory and atomic theory by Bohr, Kramers, and Slater resulted in the following scientific situation:

According to the basic postulates of the quantum theory, an atomic system is capable of assuming discrete, stationary states, and therefore discrete energy values; in terms of the energy of the atom the emission and absorption of light by such a system occurs abruptly, in the form of impulses. On the other hand, the visualizable properties of the emitted radiation are described by a wave field, the frequency of which is associated with the difference in energy between the initial and final states of the atom by the relation

$$E_1 - E_2 = h\nu$$

To each stationary state of an atom corresponds a whole complex of parameters which specify the probability of transition from this state to another. There is no direct relation between the radiation classically emitted by an orbiting electron and those parameters defining the probability of emission; nevertheless Bohr's principle of correspondence enables a specific term of the Fourier expansion of the classical path to be assigned to each transition of the atom, and the probability for the particular transition follows qualitatively similar laws as the intensity of those Fourier components. Although therefore in the researches carried out by Rutherford, Bohr, Sommerfeld and others, the comparison of the atom with a planetary system of electrons leads to a qualitative interpretation of the optical and chemical properties of atoms, nevertheless the fundamental dissimilarity between the atomic spectrum and the classical spectrum of an electron system imposes the need to relinquish the concept-of an electron path and to forego a visual description of the atom.

The experiments necessary to define the electron-path concept also furnish an important aid in revising it. The most obvious answer to the question how the orbit of an electron in its path within the atom could be observed namely, will perhaps be to use a microscope of extreme resolving power. But since the specimen in this microscope would have to be illuminated with light having an extremely short wavelength, the first light quantum from the light source to reach the electron and pass into the observer's eye would eject the electron completely from its path in accordance with the laws of the Compton effect. Consequently only one point of the path would be observable experimentally at any one time.

In this situation, therefore, the obvious policy was to relinquish at first the concept of electron paths altogether, despite its substantiation by Wilson's experiments, and, as it were, to attempt subsequently how much of the electron-path concept can be carried over into quantum mechanics.

In the classical theory the specification of frequency, amplitude, and phase of all the light waves emitted by the atom would be fully equivalent to specifying its electron path. Since from the amplitude and phase of an emitted wave the coefficients of the appropriate term in the Fourier expansion of the electron path can be derived without ambiguity, the complete electron path therefore can be derived from a knowledge of all amplitudes and phases. Similarly, in quantum mechanics, too, the whole complex of amplitudes and phases of the radiation emitted by the atom can be regarded as a complete description of the atomic system, although its interpretation in the sense of an electron path inducing the radiation is impossible. In quantum mechanics, therefore, the place of the electron coordinates is taken by a complex of parameters corresponding to the Fourier coefficients of classical motion along a path. These, however, are no longer classified by the energy of state and the number of the corresponding harmonic vibration, but are in each case associated with two stationary states of the atom, and are a measure for the transition probability of the atom from one stationary state to another. A complex of coefficients of this type is comparable with a matrix such as occurs in linear algebra. In exactly the same way each parameter of classical mechanics, e.g. the momentum or the energy of the electrons, can then be assigned a corresponding matrix in quantum mechanics. To proceed from here beyond a mere description of the empirical state of affairs it was necessary to associate systematically the matrices assigned to the various parameters in the same way as the corresponding parameters in classical mechanics are associated by equations of motions. When, in the interest of achieving the closest possible correspondence between classical and quantum mechanics, the addition and multiplication of Fourier series were tentatively taken as the example for the addition and multiplication of the quantum-theory complexes, the product of two parameters represented by matrices appeared to be most naturally represented by the product matrix in the sense of linear algebra- an assumption already suggested by the formalism of the Kramers-Ladenburg dispersion theory.

It thus seemed consistent simply to adopt in quantum mechanics the equations of motion of classical physics, regarding them as a relation between the matrices representing the classicalvariables. The Bohr- Sommerfeld quantum conditions could also be re-interpreted in a relation between the matrices, and together with the equations of motion they were sufficient to define all matrices and hence the experimentally observable properties of the atom.

Born, Jordan, and Dirac deserve the credit for expanding the mathematical scheme outlined above into a consistent and practically usable theory. These investigators observed in the first place that the quantum conditions can be written as commutation relations between the matrices representing the momenta and the coordinates of the electrons, to yield the equations (p_r, momentum matrices; q_r, coordinate matrices) :

$$p_r q_s - q_s p_r = \frac{h}{2\pi i}\,\delta_{rs} \qquad q_r q_s - q_s q_r = 0 \qquad p_r p_s - p_s p_r = 0$$

$$\delta_{rs} = \begin{cases} 1 \text{ for } r = s \\ 0 \text{ for } r \neq s \end{cases}$$

By means of these commutation relations they were able to detect in quantum mechanics as well the laws which were fundamental to classical mechanics : the invariability in time of energy, momentum, and angular momentum.

The mathematical scheme so derived thus ultimately bears an extensive formal similarity to that of the classical theory, from which it differs outwardly by the commutation relations which, moreover, enabled the equations of motion to be derived from the Hamiltonian function.

In the physical consequences, however, there are very profound differences between quantum mechanics and classical mechanics which impose the need for a thorough discussion of the physical interpretation of quantum mechanics. As hitherto defined, quantum mechanics enables the radiation emitted by the atom, the energy values of the stationary states, and other parameters characteristic for the stationary states to be treated. The theory hence complies with the experimental data contained in atomic spectra. In all those cases, however, where a visual description is required of a transient event, e.g. wheninterpreting Wilson photographs, the formalism of the theory does not seem to allow an adequate representation of the experimental state of affairs. At this point Schrödinger's wave mechanics, meanwhile developed on the basis of de Broglie's theses, came to the assistance of quantum mechanics.

In the course of the studies which Mr. Schrödinger will report here himself he converted the determination of the energy values of an atom into an eigenvalue problem defined by a boundary-value problem in the coordinate space of the particular atomic system. After Schrödinger had shown the mathematical equivalence of wave mechanics, which he had discovered, with quantum mechanics, the fruitful combination of these two different areas of physical ideas resulted in an extraordinary broadening and enrichment of the formalism of the quantum theory. Firstly it was only wave mechanics which made possible the mathematical treatment of complex atomic systems, secondly analysis of the connection between the two theories led to what is known as the transformation theory developed by Dirac and Jordan. As it is impossible within the limits of the present lecture to give a detailed discussion of the mathematical structure of this theory, I should just like to point out its fundamental physical significance. Through the adoption of the physical principles of quantum mechanics into its expanded formalism, the transformation theory made it possible in completely general terms to calculate for atomic systems the probability for the occurrence of a particular, experimentally ascertainable, phenomenon under given experimental conditions. The hypothesis conjectured in the studies on the radiation theory and enunciated in precise terms in Born's collision theory, namely that the wave function governs the probability for the presence of a corpuscle, appeared to be a special case of a more general pattern of laws and to be a natural consequence of the fundamental assumptions of quantum mechanics. Schrödinger, and in later studies Jordan, Klein, and Wigner as well, had succeeded in developing as far as permitted by the principles of the quantum theory de Broglie's original concept of visualizable matter waves occurring in space and time, a concept formulated even before the development of quantum mechanics. But for that the connection between Schrödinger's concepts and de Broglie's original thesis would certainly have seemed a looser one by this statistical interpretation of wave mechanics and by the greater emphasis on the fact that Schrödinger's theory is concerned with waves in multidimensional space. Before proceeding to discuss the explicit significance of quantum mechanics it is perhaps right for me to deal briefly with this question as to the existence of matter waves in three-dimensional space, since the solution to this problem was only achieved by combining wave and quantum mechanics.

A long time before quantum mechanics was developed Pauli had inferred from the laws in the Periodic System of the elements the well-known principle that a particular quantum state can at all times be occupied by only a single electron. It proved possible to transfer this principle to quantum mechanics on the basis of what at first sight seemed a surprising result: the entire complex of stationary states which an atomic system is capable of adopting breaks down into definite classes such that an atom in a state belonging to one class can never change into a state belonging to another class under the action of whatever perturbations. As finally clarified beyond question by the studies of Wigner and Hund, such a class of states is characterized by a defmite symmetry characteristic of the Schrödinger eigenfunction with respect to the transposition of the coordinates of two electrons. Owing to the fundamental identity of electrons, any external perturbation of the atom remains unchanged when two electrons are exchanged and hence causes no transitions between states of various classes. The Pauli principle and the Fermi-Dirac statistics derived from it are equivalent with the assumption that only that class of stationary states is achieved in nature in which the eigenfunction changes its sign when two electrons are exchanged. According to Dirac, selecting the symmetrical system of terms would lead not to the Pauli principle, but to Bose-Einstein electron statistics.

Between the classes of stationary states belonging to the Pauli principle or to Bose-Einstein statistics, and de Broglie's concept of matter waves there is a peculiar relation. A spatial wave phenomenon can be treated according to the principles of the quantum theory by analysing it using the Fourier theorem and then applying to the individual Fourier component of the wave motion, as a system having one degree of freedom, the normal laws of quantum mechanics. Applying this procedure for treating wave phenomena by the quantum theory, a procedure that has also proved fruitful in Dirac's studies of the theory of radiation, to de Broglie's matter waves, exactly the same results are obtained as in treating a whole complex of material particles according to quantum mechanics and selecting the symmetrical system of terms. Jordan and Klein hold that the two methods are mathematically equivalent even if allowance is also made for the interaction of the electrons, i.e. if the field energy originating from the continuous space charge is included in the calculation in de Broglie's wave theory. Schrödinger's considerations of the energy-momentum tensor assigned to the matter waves can then also be adopted in this theory as consistent components of the formalism. The studies of Jordan and Wigner show that modifying the commutation relations underlying this quantum theory of waves results in a formalism equivalent to that of quantum mechanics based on the assumption of Pauli's exclusion principle.

These studies have established that the comparison of an atom with a planetary system composed of nucleus and electrons is not the only visual picture of how we can imagine the atom. On the contrary, it is apparently no less correct to compare the atom with a charge cloud and use the correspondence to the formalism of the quantum theory borne by this concept to derive qualitative conclusions about the behaviour of the atom. However, it is the concern of wave mechanics to follow these consequences.

Reverting therefore to the formalism of quantum mechanics; its application to physical problems is justified partly by the original basic assumptions of the theory, partly by its expansion in the transformation theory on the basis of wave mechanics, and the question is now to expose the explicit significance of the theory by comparing it with classical physics.

In classical physics the aim of research was to investigate objective processes occurring in space and time, and to discover the laws governing their progress from the initial conditions. In classical physics a problem was considered solved when a particular phenomenon had been proved to occur objectively in space and time, and it had been shown to obey the general rules of classical physics as formulated by differential equations. The manner in which the knowledge of each process had been acquired, what observations may possibly have led to its experimental determination, was completely immaterial, and it was also immaterial for the consequences of the classical theory, which possible observations were to verify the predictions of the theory. In the quantum theory, however, the situation is completely different. The very fact that the formalism of quantum mechanics cannot be interpreted as visual description of a phenomenon occurring in space and time shows that quantum mechanics is in no way concerned with the objective determination of space-time phenomena. On the contrary, the formalism of quantum mechanics should be used in such a way that the probability for the outcome of a further experiment may be concluded from the determination of an experimental situation in an atomic system, providing that the system is subject to no perturbations other than those necessitated by performing the two experiments. The fact that the only definite known result to be ascertained after the fullest possible experimental investigation of the system is the probability for a certain outcome of a second experiment shows, however, that each observation must entail a discontinuous change in the formalism describing the atomic proces sand therefore also a discontinuous change in the physical phenomenon itself. Whereas in the classical theory the kind of observation has no bearing on the event, in the quantum theory the disturbance associated with each observation of the atomic phenomenon has a decisive role. Since, furthermore, the result of an observation as a rule leads only to assertions about the probability of certain results of subsequent observations, the fundamentally unverifiable part of each perturbation must, as shown by Bohr, be decisive for the non-contradictory operation of quantum mechanics. This difference between classical and atomic physics is understandable, of course, since for heavy bodies such as the planets moving around the sun the pressure of the sunlight which is reflected at their surface and which is necessary for them to be observed is negligible; for the smallest building units of matter, however, owing to their low mass, every observation has a decisive effect on their physical behaviour.

The perturbation of the system to be observed caused by the observation is also an important factor in determining the limits within which a visual description of atomic phenomena is possible. If there were experiments which permitted accurate measurement of all the characteristics of an atomic system necessary to calculate classical motion, and which, for example, supplied accurate values for the location and velocity of each electron in the system at a particular time, the result of these experiments could not be utilized at all in the formalism, but rather it would directly contradict the formalism. Again, therefore, it is clearly that fundamentally unverifiable part of the perturbation of the system caused by the measurement itself which hampers accurate ascertainment of the classical characteristics and thus permits quantum mechanics to be applied. Closer examination of the formalism shows that between the accuracy with which the location of a particle can be ascertained and the accuracy with which its momentum can simultaneously be known, there is a relation according to which the product of the probable errors in the measurement of the location and momentum is invariably at least as large as Planck's constant divided by 4π. In a very general form, therefore, we should have

$$\Delta p \, \Delta q \geqslant \frac{h}{4\pi}$$

where p and q are canonically conjugated variables. These uncertainty relations for the results of the measurement of classical variables form the necessary conditions for enabling the result of a measurement to be expressed in the formalism of the quantum theory. Bohr has shown in a series of examples how the perturbation necessarily associated with each observation indeed ensures that one cannot go below the limit set by the uncertainty relations. He contends that in the final analysis an uncertainty introduced by the concept of measurement itself is responsible for part of that perturbation remaining fundamentally unknown. The experimental determination of whatever space-time events invariably necessitates a fixed frame - say the system of coordinates in which the observer is at rest - to which all measurements are referred. The assumption that this frame is <<fixed>> implies neglecting its momentum from the outset, since <<fixed>> implies nothing other, of course, than that any transfer of momentum to it will evoke no perceptible effect. The fundamentally necessary uncertainty at this point is then transmitted via the measuring apparatus into the atomic event.

Since in connection with this situation it is tempting to consider the possibility of eliminating all uncertainties by amalgamating the object, the measuring apparatuses, and the observer into one quantum-mechanical system, it is important to emphasize that the act of measurement is necessarily visualizable, since, of course, physics is ultimately only concerned with the systematic description of space-time processes. The behaviour of the observer as well as his measuring apparatus must therefore be discussed according to the laws of classical physics, as otherwise there is no further physical problem whatsoever. Within the measuring apparatus, as emphasized by Bohr, all events in the sense of the classical theory will therefore be regarded as determined, this also being a necessary condition before one can, from a result of measurements, unequivocally conclude what has happened. In quantum theory, too, the scheme of classical physics which objectifies the results of observation by assuming in space and time processes obeying laws is thus carried through up to the point where the fundamental limits are imposed by the unvisualizable character of the atomic events symbolized by Planck's constant. A visual description for the atomic events is possible only within certain limits of accuracy - but within these limits the laws of classical physics also still apply. Owing to these limits of accuracy as defined by the uncertainty relations, moreover, a visual picture of the atom free from ambiguity has not been determined. On the contrary the corpuscular and the wave concepts are equally serviceable as a basis for visual interpretation.

The laws of quantum mechanics are basically statistical. Although the parameters of an atomic system are determined in their entirety by an experiment, the result of a future observation of the system is not generally accurately predictable. But at any later point of time there are observations which yield accurately predictable results. For the other observations only the probability for a particular outcome of the experiment can be given. The degree of certainty which still attaches to the laws of quantum mechanics is, for example, responsible for the fact that the principles of conservation for energy and momentum still hold as strictly as ever. They can be checked with any desired accuracy and will then be valid according to the accuracy with which they are checked. The statistical character of the laws of quantum mechanics, however, becomes apparent in that an accurate study of the energetic conditions renders it impossible to pursue at the same time a particular event in space and time.

For the clearest analysis of the conceptual principles of quantum mechanics we are indebted to Bohr who, in particular, applied the concept of complementarity to interpret the validity of the quantum-mechanical laws. The uncertainty relations alone afford an instance of how in quantum mechanics the exact knowledge of one variable can exclude the exact knowledge of another. This complementary relationship between different aspects of one and the same physical process is indeed characteristic for the whole structure of quantum mechanics. I had just mentioned that, for example, the determination of energetic relations excludes the detailed description of space-time processes. Similarly, the study of the chemical properties of a molecule is complementary to the study of the motions of the individual electrons in the molecule, or the observation of interference phenomena complementary to the observation of individual light quanta. Finally, the areas of validity of classical and quantum mechanics can be marked off one from the other as follows: Classical physics represents that striving to learn about Nature in which essentially we seek to draw conclusions about objective processes from observations and so ignore the consideration of the influences which every observation has on the object to be observed; classical physics, therefore, has its limits at the point from which the influence of the observation on the event can no longer be ignored. Conversely, quantum mechanics makes possible the treatment of atomic processes by partially foregoing their space-time description and objectification.

So as not to dwell on assertions in excessively abstract terms about the interpretation of quantum mechanics, I would like briefly to explain with a well-known example how far it is possible through the atomic theory to achieve an understanding of the visual processes with which we are concerned in daily life. The interest of research workers has frequently been focused on the phenomenon of regularly shaped crystals suddenly forming from a liquid, e.g. a supersaturated salt solution. According to the atomic theory the forming force in this process is to a certain extent the symmetry characteristic of the solution to Schrödinger's wave equation, and to that extent crystallization is explained by the atomic theory. Nevertheless this process retains a statistical and - one might almost say - historical element which cannot be further reduced: even when the state of the liquid is completely known before crystallization, the shape of the crystal is not determined by the laws of quantum mechanics. The formation of regular shapes is just far more probable than that of a shapeless lump. But the ultimate shape owes its genesis partly to an element of chance which in principle cannot be analysed further.

Before closing this report on quantum mechanics, I may perhaps be allowed to discuss very briefly the hopes that may be attached to the further development of this branch of research. It would be superfluous to mention that the development must be continued, based equally on the studies of de Broglie, Schrödinger, Born, Jordan, and Dirac. Here the attention of the research workers is primarily directed to the problem of reconciling the claims of the special relativity theory with those of the quantum theory. The extraordinary advances made in this field by Dirac about which Mr. Dirac will speak here, meanwhile leave open the question whether it will be possible to satisfy the claims of the two theories without at the same time determining the Sommerfeld fine-structure constant. The attempts made hitherto to achieve a relativistic formulation of the quantum theory are all based on visual concepts so close to those of classical physics that it seems impossible to determine the fine-structure constant within this system of concepts. The expansion of the conceptual system under discussion here should, furthermore, be closely associated with the further development of the quantum theory of wave fields, and it appears to me as if this formalism, notwithstanding its thorough study by a number of workers (Dirac, Pauli, Jordan, Klein, Wigner, Fermi) has still not been completely exhausted. Important pointers for the further development of quantum mechanics also emerge from the experiments involving the structure of the atomic nuclei. From their analysis by means of the Gamow theory, it would appear that between the elementary particles of the atomic nucleus forces are at work which differ somewhat in type from the forces determining the structure of the atomic shell; Stem's experiments seem, furthermore, to indicate that the behaviour of the heavy elementary particles cannot be represented by the formalism of Dirac's theory of the electron. Future research will thus have to be prepared for surprises which may otherwise come both from the field of experience of nuclear physics as well as from that of cosmic radiation. But however the development proceeds in detail, the path so far traced by the quantum theory indicates that an understanding of those still unclarified features of atomic physics can only be acquired by foregoing visualization and objectification to an extent greater than that customary hitherto. We have probably no reason to regret this, because the thought of the great epistemological difficulties with which the visual atom concept of earlier physics had to contend gives us the hope that the abstracter atomic physics developing at present will one day fit more harmoniously into the great edifice of Science.

Biography

Werner Heisenberg was born on 5th December, 1901, at Würzburg. He was the son of Dr. August Heisenberg and his wife ‘Annie Wecklein. His father later became Professor of the Middle and Modern Greek languages in the University of Munich. It was probably due to his influence that Heisenberg remarked, when the Japanese physicist Yukawa discovered the particle now known as the meson and the term <<mesotron>> was proposed for it, that the Greek word <<mesos>> has no <<tr>> in it, with the result that the name <<mesotron>> was changed to <<meson>>.

Heisenberg went to the Maximilian school at Munich until 1920, when he went to the University of Munich to study physics under Sommerfeld, Wien Pringsheim, and Rosenthal. During the winter of 1922-1923 he went to Göttingen to study physics under Max Born, Franck, and Hilbert. In 1923 he took his Ph.D. at the University of Munich and then became Assistant to Max Born at the University of Göttingen, and in 1924 he gamed the *venia legendi* at that University.

From 1924 until 1925 he worked, with a Rockefeller Grant, with Niels Bohr, at the University of Copenhagen, returning for the summer of 1925 to Göttingen.

In 1926 he was appointed Lecturer in Theoretical Physics at the University of Copenhagen under Niels Bohr and in 1927, when he was only 26, he was appointed Professor of Theoretical Physics at the University of Leipzig.

In 1929 he went on a lecture tour to the United States, Japan, and India.

In 1941 he was appointed Professor of Physics at the University of Berlin and Director of the Kaiser Wilhelm Institute for Physics there.

At the end of the Second World War he, and other German physicists, were taken prisoner by American troops and sent to England, but in 1946 he returned to Germany and reorganized, with his colleagues, the Institute for Physics at Göttingen. This Institute was, in 1948, renamed the Max Planck Institute for Physics.

In 1948 Heisenberg stayed for some months in Cambridge, England, to give lectures, and in 1950 and 1954 he was invited to lecture in the United

States. In the winter of 1955-1956 he gave the Gifford Lectures at the University of St. Andrews, Scotland, these lectures being subsequently published as a book.

During 1955 Heisenberg was occupied with preparations for the removal of the Max Planck Institute for Physics to Munich. Still Director of this Institute, he went with it to Munich and in 1958 he was appointed Professor of Physics in the University of Munich. His Institute was then being renamed the Max Planck Institute for Physics and Astrophysics.

Heisenberg's name will always be associated with his theory of quantum mechanics, published in 1925, when he was only 23 years old. For this theory and the applications of it which resulted especially in the discovery of allotropic forms of hydrogen, Heisenberg was awarded the Nobel Prize for Physics for 1932.

His new theory was based only on what can be observed, that is to say, on the radiation emitted by the atom. We cannot, he said, always assign to an electron a position in space at a given time, nor follow it in its orbit, so that we cannot assume that the planetary orbits postulated by Niels Bohr actually exist. Mechanical quantities, such as position, velocity, etc. should be represented, not by ordinary numbers, but by abstract mathematical structures called <<matrices>> and he formulated his new theory in terms of matrix equations.

Later Heisenberg stated his famous *principle* of *uncertainty,* which lays it down that the determination of the position and momentum of a mobile particle necessarily contains errors the product of which cannot be less than the quantum constant h and that, although these errors are negligible on the human scale, they cannot be ignored in studies of the atom.

From 1957 onwards Heisenberg was interested in work on problems of plasma physics and thermonuclear processes, and also much work in close collaboration with the International Institute of Atomic Physics at Geneva. He was for several years Chairman of the Scientific Policy Committee of this Institute and subsequently remained a member of this Committee.

When he became, in 1953, President of the Alexander von Humboldt Foundation, he did much to further the policy of this Foundation, which was to invite scientists from other countries to Germany and to help them to work there.

Since 1953 his own theoretical work was concentrated on the unified field theory of elementary particles which seems to him to be the key to an understanding of the physics of elementary particles.

Apart from many medals and prizes, Heisenberg received an honorary doctorate of the University of Bruxelles, of the Technological University Karlsruhe, and recently (1964) of the University of Budapest; he is also recipient of the Order of Merit of Bavaria, and the Grand Cross for Federal Services with Star (Germany). He is a Fellow of the Royal Society of London and a Knight of the Order of Merit (Peace Class). He is a member of the Academies of Sciences of Göttingen, Bavaria, Saxony, Prussia, Sweden, Rumania, Norway, Spain, The Netherlands, Rome (Pontificial), the German Akademie der Naturforscher Leopoldina (Halle), the Accademia dei Lincei (Rome), and the American Academy of Sciences. During 1949-1951 he was President of the Deutsche Forschungsrat (German Research Council) and in 1953 he became President of the Alexander von Humboldt Foundation.

One of his hobbies is classical music: he is a distinguished pianist. In 1937 Heisenberg married Elisabeth Schumacher. They have seven children, and live in Munich.

ERWIN SCHRÖDINGER

The fundamental idea of wave mechanics

Nobel Lecture, December 12, 1933

On passing through an optical instrument, such as a telescope or a camera lens, a ray of light is subjected to a change in direction at each refracting or reflecting surface. The path of the rays can be constructed if we know the two simple laws which govern the changes in direction: the law of refraction which was discovered by Snellius a few hundred years ago, and the law of reflection with which Archimedes was familiar more than 2,000 years ago. As a simple example, Fig. 1 shows a ray A-B which is subjected to refraction at each of the four boundary surfaces of two lenses in accordance with the law of Snellius.

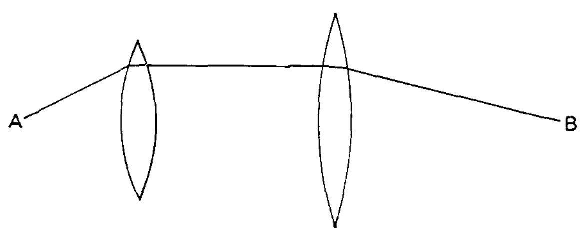

Fig. 1.

Fermat defined the total path of a ray of light from a much more general point of view. In different media, light propagates with different velocities, and the radiation path gives the appearance as if the light must arrive at its destination *as quickly as* possible. (Incidentally, it is permissible here to consider *any two* points along the ray as the starting- and end-points.) The least deviation from the path actually taken would mean a delay. This is the famous Fermat *principle of the shortest light time,* which in a marvellous manner determines the entire fate of a ray of light by a single statement and also includes the more general case, when the nature of the medium varies not suddenly at individual surfaces, but gradually from place to place. The atmosphere of the earth provides an example. The more deeply a ray of light penetrates into it from outside, the more slowly it progresses in an increasingly denser air. Although the differences in the speed of propagation are infinitesimal, Fermat's principle in these circumstances demands that the light ray should curve earthward (see Fig. 2), so that it remains a little longer in the higher <<faster>> layers and reaches its destination more quickly than by the shorter straight path (broken line in the figure; disregard the square,

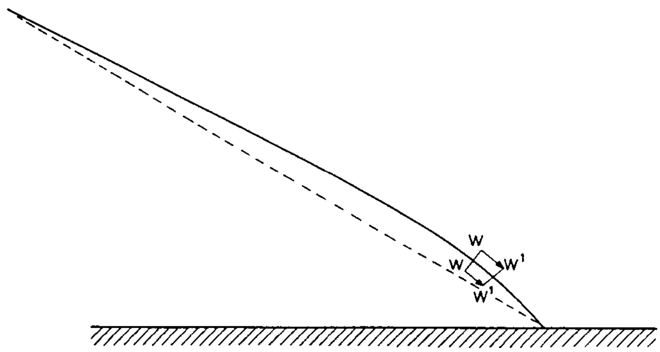

Fig. 2.

WWW^1W^1 for the time being). I think, hardly any of you will have failed to observe that the sun when it is deep on the horizon appears to be not circular but flattened: its vertical diameter looks to be shortened. This is a result of the curvature of the rays.

According to the wave theory of light, the light rays, strictly speaking, have only fictitious significance. They are not the physical paths of some particles of light, but are a mathematical device, the so-called orthogonal trajectories of wave surfaces, imaginary guide lines as it were, which point in the direction normal to the wave surface in which the latter advances (cf. Fig. 3 which shows the simplest case of concentric spherical wave surfaces and accordingly rectilinear rays, whereas Fig. 4 illustrates the case of curved

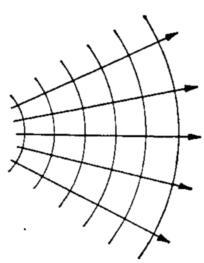

Fig. 3.

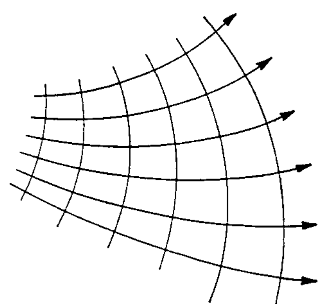

Fig. 4.

rays). It is surprising that a general principle as important as Fermat's relates directly to these mathematical guide lines, and not to the wave surfaces, and one might be inclined for this reason to consider it a mere mathematical curiosity. Far from it. It becomes properly understandable only from the point of view of wave theory and ceases to be a divine miracle. From the wave point of view, the so-called *curvature* of the light ray is far more readily understandable as a *swerving* of the wave surface, which must obviously occur when neighbouring parts of a wave surface advance at different speeds; in exactly the same manner as a company of soldiers marching forward will carry out the order <<right incline>> by the men taking steps ofvarying lengths, the right-wing man the smallest, and the left-wing man the longest. In atmospheric refraction of radiation for example (Fig. 2) the section of wave surface WW must necessarily swerve to the right towards W^1W^1 because its left half is located in slightly higher, thinner air and thus advances more rapidly than the right part at lower point. (In passing, I wish to refer to one point at which the *Snellius'* view fails. A horizontally emitted light ray should remain horizontal because the refraction index does not vary in the horizontal direction. In truth, a horizontal ray curves more strongly than any other, which is an obvious consequence of the theory of a swerving wave front.) On detailed examination the Fermat principle is found to be completely *tantamount* to the trivial and obvious statement that-given local distribution of light velocities-the wave front must swerve in the manner indicated. I cannot prove this here, but shall attempt to make it plausible. I would again ask you to visualize a rank of soldiers marching forward. To ensure that the line remains dressed, let the men be connected by a long rod which each holds firmly in his hand. No orders as to direction are given; the only order is: let each man march or run as fast as he can. If the nature of the ground varies slowly from place to place, it will be now the right wing, now the left that advances more quickly, and changes in direction will occur spontaneously. After some time has elapsed, it will be seen that the entire path travelled is not rectilinear, but somehow curved. That this curved path is exactly that by which the destination attained at any moment could be attained *most rapidly* according to the nature of the terrain, is at least quite plausible, since each of the men did his best. It will also be seen that the swerving also occurs invariably in the direction in which the terrain is worse, so that it will come to look in the end as if the men had intentionally <<by-passed>> a place where they would advance slowly.

The Fermat principle thus appears to be the trivial quintessence of the wave theory. It was therefore a memorable occasion when Hamilton made the discovery that the true movement of mass points in a field of forces (e.g. of a planet on its orbit around the sun or of a stone thrown in the gravitational field of the earth) is also governed by a very similar general principle, which carries and has made famous the name of its discoverer since then. Admittedly, the Hamilton principle does not say exactly that the mass point chooses the quickest way, but it does say something so similar - the analogy with the principle of the shortest travelling time of light is so close, that one was faced with a puzzle. It seemed as if Nature had realized one and the same law twice by entirely different means: first in the case of light, by means of a fairly obvious play of rays; and again in the case of the mass points, which was anything but obvious, unless somehow wave nature were to be attributed to them also. And this, it seemed impossible to do. Because the <<mass points>> on which the laws of mechanics had really been confirmed experimentally at that time were only the large, visible, sometimes very large bodies, the planets, for which a thing like <<wave nature>> appeared to be out of the question.

The smallest, elementary components of matter which we today, much more specifically, call <<mass points>>, were purely hypothetical at the time. It was only after the discovery of radioactivity that constant refinements of methods of measurement permitted the properties of these particles to be studied in detail, and now permit the paths of such particles to be photographed and to be measured very exactly (stereophotogrammetrically) by the brilliant method of C. T. R. Wilson. As far as the measurements extend they confirm that the same mechanical laws are valid for particles as for large bodies, planets, etc. However, it was found that neither the molecule nor the individual atom can be considered as the <<ultimate component a: but even the atom is a system of highly complex structure. Images are formed in our minds of the structure of atoms *consisting* ofparticles, images which seem to have a certain similarity with the planetary system. It was only natural that the attempt should at first be made to consider as valid the same laws of motion that had proved themselves so amazingly satisfactory on a large scale. In other words, Hamilton's mechanics, which, as I said above, culminates in the Hamilton principle, were applied also to the <<inner life>> of the atom. That there is a very close analogy between Hamilton's principle and Fermat's optical principle had meanwhile become all but forgotten. If it was remembered, it was considered to be nothing more than a curious trait of the mathematical theory.

Now, it is very difficult, without further going into details, to convey a proper conception of the success or failure of these classical-mechanical images of the atom. On the one hand, Hamilton's principle in particular proved to be the most faithful and reliable guide, which was simply indispensable; on the other hand one had to suffer, to do justice to the facts, the rough interference of entirely new incomprehensible postulates, of the so-called quantum conditions and quantum postulates. Strident disharmony in the symphony of classical mechanics-yet strangely familiar-played as it were on the same instrument. In mathematical terms we can formulate this as follows: whereas the Hamilton principle merely postulates that a given integral must be a minimum, without the numerical value of the minimum being established by this postulate, it is now demanded that the numerical value of the minimum should be restricted to integral multiples of a universal natural constant, Planck's quantum of action. This incidentally. The situation was fairly desperate. Had the old mechanics failed completely, it would not have been so bad. The way would then have been free to the development of a new system ofmechanics. As it was, one was faced with the difficult task of saving the soul of the old system, whose inspiration clearly held sway in this microcosm, while at the same time flattering it as it were into accepting the quantum conditions not as gross interference but as issuing from its own innermost essence.

The way out lay just in the possibility, already indicated above, of attributing to the Hamilton principle, also, the operation of a wave mechanism on which the point-mechanical processes are essentially based, just as one had long become accustomed to doing in the case of phenomena relating to light and of the Fermat principle which governs them. Admittedly, the individual path of a mass point loses its proper physical significance and becomes as fictitious as the individual isolated ray of light. The essence of the theory, the minimum principle, however, remains not only intact, but reveals its true and simple meaning only under the wave-like aspect, as already explained. Strictly speaking, the new theory is in fact not *new*, it is a completely organic development, one might almost be tempted to say a more elaborate exposition, of the old theory.

How was it then that this new more <<elaborate>> exposition led to notably different results; what enabled it, when applied to the atom, to obviate difficulties which the old theory could not solve? What enabled it to render gross interference acceptable or even to make it its own?

Again, these matters can best be illustrated by analogy with optics. Quite properly, indeed, I previously called the Fermat principle the quintessence of the wave theory of light: nevertheless, it cannot render dispensible a more exact study of the wave process itself. The so-called refraction and interference phenomena of light can only be understood if we trace the wave process in detail because what matters is not only the eventual destination of the wave, but also whether at a given moment it arrives there with a wave peak or a wave trough. In the older, coarser experimental arrangements, these phenomena occurred as small details only and escaped observation. Once they were noticed and were interpreted correctly, by means of waves, it was easy to devise experiments in which the wave nature of light finds expression not only in small details, but on a very large scale in the entire character of the phenomenon.

Allow me to illustrate this by two examples, first, the example of an optical instrument, such as telescope, microscope, etc. The object is to obtain a sharp image, i.e. it is desired that all rays issuing from a point should be reunited in a point, the so-called focus (cf. Fig. 5 a). It was at first believed that it was only geometrical-optical difficulties which prevented this: they are indeed considerable. Later it was found that even in the best designed instru-

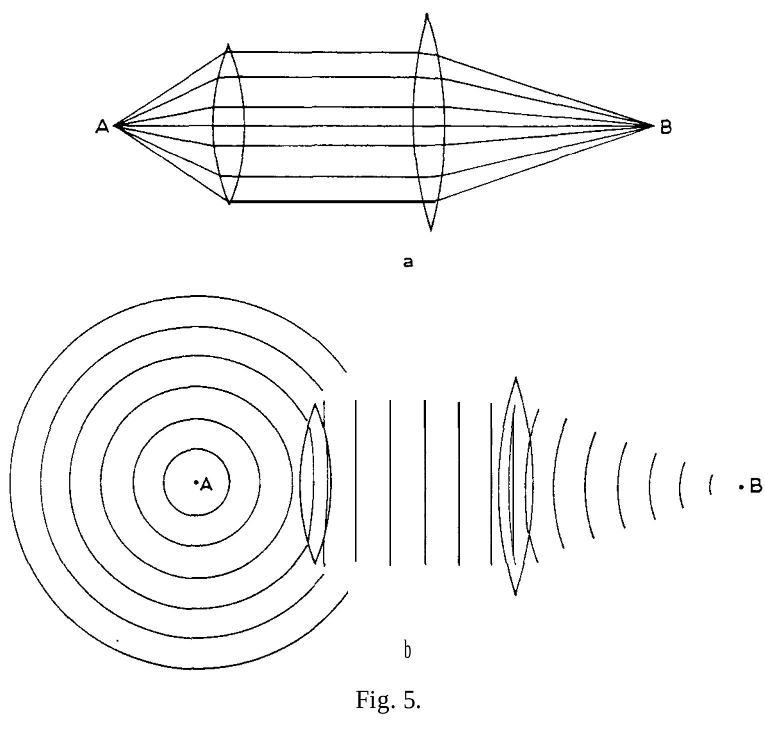

Fig. 5.

ments focussing of the rays was considerably inferior than would be expected if each ray exactly obeyed the Fermat principle independently of the neighbouring rays. The light which issues from a point and is received by the instrument is reunited behind the instrument not in a single point any more, but is distributed over a small circular area, a so-called diffraction disc, which, otherwise, is in most cases a circle only because the apertures and lens contours are generally circular. For, the cause of the phenomenon which we call *diffraction* is that not all the spherical waves issuing from the object point can be accommodated by the instrument. The lens edges and any apertures merely cut out a part of the wave surfaces (cf. Fig. 5b) and-if you will permit me to use a more suggestive expression-the injured margins resist rigid unification in a point and produce the somewhat blurred or vague image. The degree of blurring is closely associated with the wavelength of the light and is completely inevitable because of this deep-seated theoretical relationship. Hardly noticed at first, it governs and restricts the performance of the modern microscope which has mastered all other errors of reproduction. The images obtained of structures not much coarser or even still finer than the wavelengths of light are only remotely or not at all similar to the original.

A second, even simpler example is the shadow of an opaque object cast on a screen by a small point light source. In order to construct the shape of the shadow, each light ray must be traced and it must be established whether or not the opaque object prevents it from reaching the screen. The *margin* of the shadow is formed by those light rays which only just brush past the edge of the body. Experience has shown that the shadow margin is not absolutely sharp even with a point-shaped light source and a sharply defined shadow-casting object. The reason for this is the same as in the first example. The wave front is as it were bisected by the body (cf. Fig. 6) and the traces of this injury result in blurring of the margin of the shadow which would be incomprehensible if the individual light rays were independent entities advancing independently of one another without reference to their neighbours.

This phenomenon - which is also called diffraction-is not as a rule very noticeable with large bodies. But if the shadow-casting body is very small at least in one dimension, diffraction finds expression firstly in that no proper shadow is formed at all, and secondly - much more strikingly - in that the small body itself becomes as it were its own source of light and radiates light in all directions (preferentially to be sure, at small angles relative to the inci-

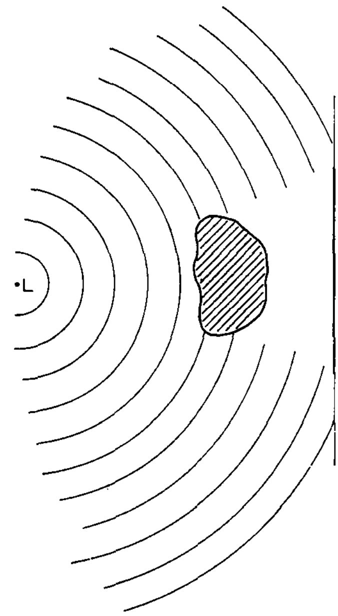

Fig. 6.

dent light). All of you are undoubtedly familiar with the so-called <<motes of dust>> in a light beam falling into a dark room. Fine blades of grass and spiders' webs on the crest of a hill with the sun behind it, or the errant locks of hair of a man standing with the sun behind often light up mysteriously by diffracted light, and the visibility of smoke and mist is based on it. It comes not really from the body itself, but from its immediate surroundings, an area in which it causes considerable interference with the incident wave fronts. It is interesting, and important for what follows, to observe that the area of interference always and in every direction has at least the extent of one or a few wavelengths, no matter how small the disturbing particle may be. Once again, therefore, we observe a close relationship between the phenomenon of diffraction and wavelength. This is perhaps best illustrated by reference to another wave process, i.e. sound. Because of the much greater wavelength, which is of the order of centimetres and metres, shadow formation recedes in the case of sound, and diffraction plays a major, and practically important, part: we can easily *hear* a man calling from behind a high wall or around the corner of a solid house, even if we cannot see him.

Let us return from optics to mechanics and explore the analogy to its fullest extent. In optics the old system of mechanics corresponds to intellectually operating with isolated mutually independent light rays. The new undulatory mechanics corresponds to the wave theory of light. What is gained by changing from the old view to the new is that the diffraction phenomena can be accommodated or, better expressed, what is gained is something that is strictly analogous to the diffraction phenomena of light and which on the whole must be very unimportant, otherwise the old view of mechanics would not have given full satisfaction so long. It is, however, easy to surmise that the neglected phenomenon may in some circumstances make itself very much felt, will entirely dominate the mechanical process, and will face the old system with insoluble riddles, if *the entire mechanical system is comparable in extent with the wavelengths of the <<waves of matter>>* which play the same part in mechanical processes as that played by the light waves in optical processes.

This is the reason why in these minute systems, the atoms, the old view was bound to fail, which though remaining intact as a close approximation for gross mechanical processes, but is no longer adequate for the delicate interplay in areas of the order of magnitude of one or a few wavelengths. It was astounding to observe the manner in which all those strange additional requirements developed spontaneously from the new undulatory view, whereas they had to be forced upon the old view to adapt them to the inner life of the atom and to provide some explanation of the observed facts.

Thus, the salient point of the whole matter is that the diameters of the atoms and the wavelength of the hypothetical material waves are of approximately the same order of magnitude. And now you are bound to ask whether it must be considered mere chance that in our continued analysis of the structure of matter we should come upon the order of magnitude of the wavelength at this of all points, or whether this is to some extent comprehensible. Further, you may ask, how we know that this is so, since the material waves are an entirely new requirement of this theory, unknown anywhere else. Or is it simply that this is an *assumption* which had to be made?

The agreement between the orders of magnitude is no mere chance, nor is any special assumption about it necessary; it follows automatically from the theory in the following remarkable manner. That the heavy *nucleus* of the atom is very much smaller than the atom and may therefore be considered as a point centre of attraction in the argument which follows may be considered as experimentally established by the experiments on the scattering of alpha rays done by Rutherford and Chadwick. Instead of the *electrons we* introduce hypothetical waves, whose wavelengths are left entirely open, because we know nothing about them yet. This leaves a letter, say a, indicating a still unknown figure, in our calculation. We are, however, used to this in such calculations and it does not prevent us from calculating that the nucleus of the atom must produce a kind of diffraction phenomenon in these waves, similarly as a minute dust particle does in light waves. Analogously, it follows that there is a close relationship between the extent of the area of interference with which the nucleus surrounds itself and the wavelength, and that the two are of the same order of magnitude. What this is, we have had to leave open; but the most important step now follows: we *identify the area of interference, the diffraction halo, with the atom; we assert that the atom in reality is merely the diffraction phenomenon of an electron wave captured us it were by the nucleus of the atom.* It is no longer a matter of chance that the size of the atom and the wavelength are of the same order of magnitude: it is a matter of course. We know the numerical value of neither, because we still have in our calculation the *one* unknown constant, which we called a. There are two possible ways of determining it, which provide a mutual check on one another. First, we can so select it that the manifestations of life of the atom, above all the spectrum lines emitted, come out correctly quantitatively; these can after all be measured very accurately. Secondly, we can select a in a manner such that the diffraction halo acquires the size required for the atom. These two determinations of a (of which the second is admittedly far more imprecise because <<size of the atom>> is no clearly defined term) *are in complete agreement with one another.* Thirdly, and lastly, we can remark that the constant remaining unknown, physically speaking, does not in fact have the dimension of a length, but of an action, i.e. energy x time. It is then an obvious step to substitute for it the numerical value of Planck's universal quantum of action, which is accurately known from the laws of heat radiation. It will be seen that we *return,* with the full, now considerable accuracy, *to the first* (most accurate) *determination.*

Quantitatively speaking, the theory therefore manages with a minimum of new assumptions. It contains a single available constant, to which a numerical value familiar from the older quantum theory must be given, first to attribute to the diffraction halos the right size so that they can be reasonably identified with the atoms, and secondly, to evaluate quantitatively and correctly all the manifestations of life of the atom, the light radiated by it, the ionization energy, etc.

I have tried to place before you the fundamental idea of the wave theory of matter in the simplest possible form. I must admit now that in my desire not to tangle the ideas from the very beginning, I have painted the lily. Not as regards the high degree to which all sufficiently, carefully drawn conclusions are confirmed by experience, but with regard to the conceptual ease and simplicity with which the conclusions are reached. I am not speaking here of the mathematical difficulties, which always turn out to be trivial in the end, but of the conceptual difficulties. It is, of course, easy to say that we turn from the concept of a *curved path* to a system of wave surfaces normal to it. The wave surfaces, however, even if we consider only small parts of them (see Fig. 7) include at least a narrow *bundle* of possible curved paths,

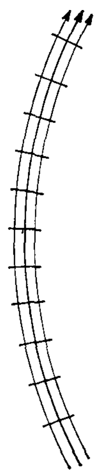

Fig. 7.

to all of which they stand in the same relationship. According to the old view, but not according to the new, one of them in each concrete individual case is distinguished from all the others which are <<only possible>>, as that <<really travelled>>. We are faced here with the full force of the logical opposition between an

either - or (point mechanics)

and a

both - and (wave mechanics)

This would not matter much, if the old system were to be dropped entirely and to be *replaced* by the new. Unfortunately, this is not the case. From the point of view of wave mechanics, the infinite array of possible point paths would be merely fictitious, none of them would have the prerogative over the others of being that really travelled in an individual case. I have, however, already mentioned that we have yet really observed such individual particle paths in some cases. The wave theory can represent this, either not at all or only very imperfectly. We find it confoundedly difficult to interpret the traces we see as nothing more than narrow bundles of equally possible paths between which the wave surfaces establish cross-connections. Yet, these cross-connections are necessary for an understanding of the diffraction and interference phenomena which can be demonstrated for the same particle with the same plausibility-and that on a large scale, not just as a consequence of the theoretical ideas about the interior of the atom, which we mentioned earlier. Conditions are admittedly such that we can always manage to make do in each concrete individual case without the two different aspects leading to different expectations as to the result of certain experiments. We cannot, however, manage to make do with such old, familiar, and seemingly indispensible terms as <<real>> or <<only possible>>; we are never in a position to say what really *is* or what really *happens,* but we can only say what will be *observed* in any concrete individual case. Will we have to be permanently satisfied with this. . . ? On principle, yes. On principle, there is nothing new in the postulate that in the end exact science should aim at nothing more than the description of what can really be observed. The question is only whether from now on we shall have to refrain from tying description to a clear hypothesis about the real nature of the world. There are many who wish to pronounce such abdication even today. But I believe that this means making things a little too easy for oneself.

I would define the present state of our knowledge as follows. The ray or the particle path corresponds to a *longitudinal* relationship of the propagation process (i.e. *in the direction* of propagation), the wave surface on the other hand to a *transversal* relationship (i.e. *norma1* to it). *Both* relationships are without doubt real; one is proved by photographed particle paths, the other by interference experiments. To combine both in a uniform system has proved impossible so far. Only in extreme cases does either the transversal, shell-shaped or the radial, longitudinal relationship predominate to such an extent that *we think* we can make do with the wave theory alone or with the particle theory alone.

Biography

Erwin Schrödinger was born on August 12, 1887, in Vienna, the only child of Rudolf Schrödinger, who was married to a daughter of Alexander Bauer, his Professor of Chemistry at the Technical College of Vienna. Erwin's father came from a Bavarian family which generations before had settled in Vienna. He was a highly gifted man with a broad education. After having finished his chemistry studies, he devoted himself for years to Italian painting. After this he took up botany, which resulted in a series of papers on plant phylogeny.

Schrödinger's wide interests dated from his school years at the Gymnasium, where he not only had a liking for the scientific disciplines, but also appreciated the severe logic of ancient grammar and the beauty of German poetry. (What he abhorred was memorizing of data and learning from books.)

From 1906 to 1906 he was a student at the University of Vienna, during which time he came under the strong influence of Fritz Hasenöhrl, who was Boltzmann's successor. It was in these years that Schrödinger acquired a mastery of eigenvalue problems in the physics of continuous media, thus laying the foundation for his future great work. Hereafter, as assistant to Franz Exner, he, together with his friend K. W. F. Kohlrausch, conducted practical work for students (without himself, as he said, learning what experimenting was). During the First World War he served as an artillery officer.

In 1920 he took up an academic position as assistant to Max Wien, followed by positions at Stuttgart (extraordinary professor), Breslau (ordinary professor), and at the University of Zurich (replacing von Laue) where he settled for six years. In later years Schrödinger looked back to his Zurich period with great pleasure-it was here that he enjoyed so much the contact and friendship of many of his colleagues, among whom were Hermann Weyl and Peter Debye. It was also his most fruitful period, being actively engaged in a variety of subjects of theoretical physics. His papers at that time dealt with specific heats of solids, with problems of thermodynamics (he was greatly interested in Boltzmann's probability theory) and of atomic spectra; in addition, he indulged in physiological studies of colour (as a result of his contacts with Kohlrausch and Exner, and of Helmholtz's lectures). His great discovery, Schrödinger's wave equation, was made at the end of this epoch-during the first half of 1926.

It came as a result of his dissatisfaction with the quantum condition in Bohr's orbit theory and his belief that atomic spectra should really be determined by some kind of eigenvalue problem. For this work he shared with Dirac the Nobel Prize for 1933.

In 1927 Schrödinger moved to Berlin as Planck's successor. Germany's capital was then a centre of great scientific activity and he enthusiastically took part in the weekly colloquies among colleagues, many of whom <<exceeding him in age and reputation>>. With Hitler's coming to power (1933), however, Schrödinger decided he could not continue in Germany. He came to England and for a while held a fellowship at Oxford. In 1936 he was offered a position at Graz, which he accepted only after much deliberation and because his longing for his native country outweighed his caution. With the annexation of Austria in 1938, he was immediately in difficulty because his leaving Germany in 1933 was taken to be an unfriendly act. Soon afterwards he managed to escape to Italy, from where he proceeded to Princeton University. After a short stay he moved to the newly created Institute for Advanced Studies in Dublin, where he became Director of the School for Theoretical Physics. He remained in Dublin until his retirement in 1955.

All this time Schrödinger continued his research and published many papers on a variety of topics, including the problem of unifying gravitation and electromagnetism, which also absorbed Einstein and which is still unsolved; (he was also the author of the well-known little book <<What is Life?>>, 1944). He remained greatly interested in the foundations of atomic physics. Schrödinger disliked the generally accepted dual description in terms of waves and particles, with a statistical interpretation for the waves, and tried to set up a theory in terms of waves only. This led him into controversy with other leading physicists.

Throughout his scientific career and also in his personal life, Schrödinger never tried to achieve a specific goal, nor did he follow any extensive project. He always found it difficult to work with others, even with his own pupils.

His unconventional way of life may probably be best illustrated by the fact that he would always carry his belongings in a rucksack on his back, and walk to the hotel from the station, even on such occasions as the Solvay Conferences in Brussels.

After his retirement he returned to an honoured position in Vienna. He died on the 4th of January, 1961, after a long illness, survived by his faithful companion, Annemarie Bertel, whom he married in 1920.

PAUL A.M. DIRAC

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

Matter has been found by experimental physicists to be made up of small particles of various kinds, the particles of each kind being all exactly alike. Some of these kinds have definitely been shown to be composite, that is, to be composed of other particles of a simpler nature. But there are other kinds which have not been shown to be composite and which one expects will never be shown to be composite, so that one considers them as elementary and fundamental.

From general philosophical grounds one would at first sight like to have as few kinds of elementary particles as possible, say only one kind, or at most two, and to have all matter built up of these elementary kinds. It appears from the experimental results, though, that there must be more than this. In fact the number of kinds of elementary particle has shown a rather alarming tendency to increase during recent years.

The situation is perhaps not so bad, though, because on closer investigation it appears that the distinction between elementary and composite particles cannot be made rigorous. To get an interpretation of some modem experimental results one must suppose that particles can be created and annihilated. Thus if a particle is observed to come out from another particle, one can no longer be sure that the latter is composite. The former may have been created. The distinction between elementary particles and composite particles now becomes a matter of convenience. This reason alone is sufficient to compel one to give up the attractive philosophical idea that all matter is made up of one kind, or perhaps two kinds of bricks.

I should like here to discuss the simpler kinds of particles and to consider *what can be inferred about them from purely theoretical arguments.* The simpler kinds of particle are:

(i) the photons or light-quanta, of which light is composed;

(ii) the electrons, and the recently discovered positrons (which appear to be a sort of mirror image of the electrons, differing from them only in the sign of their electric charge) ;

(iii) the heavier particles - protons and neutrons.

Of these, I shall deal almost entirely with the electrons and the positrons -not because they are the most interesting ones, but because in their case the theory has been developed further. There is, in fact, hardly anything that can be inferred theoretically about the properties of the others. The photons, on the one hand, are so simple that they can easily be fitted into any theoretical scheme, and the theory therefore does not put any restrictions on their properties. The protons and neutrons, on the other hand, seem to be too complicated and no reliable basis for a theory of them has yet been discovered.

The question that we must first consider is how theory can give any information at all about the properties of elementary particles. There exists at the present time a general quantum mechanics which can be used to describe the motion of any kind of particle, no matter what its properties are. The general quantum mechanics, however, is valid only when the particles have small velocities and fails for velocities comparable with the velocity of light, when effects of relativity come in. There exists no relativistic quantum mechanics (that is, one valid for large velocities) which can be applied to particles with arbitrary properties. Thus when one subjects quantum mechanics to relativistic requirements, one imposes restrictions on the properties of the particle. In this way one can deduce information about the particles from purely theoretical considerations, based on general physical principles.

This procedure is successful in the case of electrons and positrons. It is to be hoped that in the future some such procedure will be found for the case of the other particles. I should like here to outline the method for electrons and positrons, showing how one can deduce the spin properties of the electron, and then how one can infer the existence of positrons with similar spin properties and with the possibility of being annihilated in collisions with electrons.

We begin with the equation connecting the kinetic energy W and momentum p_r, (r = 1, 2, 3), of a particle in relativistic classical mechanics

$$\frac{W^2}{c^2} - p_r^2 - m^2c^2 = 0 \qquad (1)$$

From this we can get a wave equation of quantum mechanics, by letting the left-hand side operate on the wave function ψ and understanding W and p_r to be the operators $ih\partial/\partial t$ and $-ih\partial/\partial x_r$. With this understanding, the wave equation reads

$$\left[\frac{W^2}{c^2} - p_r^2 - m^2c^2\right]\psi = 0$$

Now it is a general requirement of quantum mechanics that its wave equations shall be linear in the operator W or $\partial/\partial t$, so this equation will not do. We must replace it by some equation linear in W, and in order that this equation may have relativistic invariance it must also be linear in the p's.

We are thus led to consider an equation of the type

$$\left[\frac{W}{c} - \alpha_r p_r - \alpha_0 mc\right]\psi = 0$$

This involves four new variables α_r and α_0, which are operators that can operate on ψ. We assume they satisfy the following conditions,

$$\alpha_\mu^2 = 1 \qquad \alpha_\mu\alpha_\nu + \alpha_\nu\alpha_\mu = 0$$

for

$$\mu \neq \nu \text{ and } \mu, \nu = 0, 1, 2, 3$$

and also the *a's* commute with the *p's* and *W*. These special properties for the a's make Eq. (3) to a certain extent equivalent to Eq. (2), since if we then multiply (3) on the left-hand side by $W/c + \alpha_r p_r + \alpha_0 mc$ *we* get exactly *(2)*.

The new variables *a*, which we have to introduce to get a relativistic wave equation linear in *W*, give rise to the spin of the electron. From the general principles of quantum mechanics one can easily deduce that these variables *a* give the electron a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton in the reverse direction to the angular momentum. These results are in agreement with experiment. They were, in fact, first obtained from the experimental evidence provided-by spectroscopy and afterwards confirmed by the theory,

The variables *a* also give rise to some rather unexpected phenomena concerning the motion of the electron. These have been fully worked out by Schrödinger. It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency *oscillatory* motion of small amplitude superposed on the regular motion which appears to us. As a result of this oscillatory motion, the velocity of the electron at any time equals the velocity of light. This is a prediction which cannot be directly verified by experiment, since the frequency of the oscillatory motion is so high and its amplitude is so small. But one must believe in this consequence of the theory, since other consequences of the theory which are inseparably bound up with this one, such as the law of scattering of light by an electron, are confirmed by experiment.

There is one other feature of these equations which I should now like to discuss, a feature which led to the prediction of the positron. If one looks at Eq. (1), one sees that it allows the kinetic energy W to be either a positive quantity greater than mc^2 or a negative quantity less than $-mc^2$. This result is preserved when one passes over to the quantum equation (2) or (3). These quantum equations are such that, when interpreted according to the general scheme of quantum dynamics, they allow as the possible results of a measurement of W either something greater than mc^2 or something less than $-mc^2$.

Now in practice the kinetic energy of a particle is always positive. We thus see that our equations allow of two kinds of motion for an electron, only one of which corresponds to what we are familiar with. The other corresponds to electrons with a very peculiar motion such that the faster they move, the less energy they have, and one must put energy into them to bring them to rest.

One would thus be inclined to introduce, as a new assumption of the theory, that only one of the two kinds of motion occurs in practice. But this gives rise to a difficulty, since we find from the theory that if we disturb the electron, we may cause a transition from a positive-energy state of motion to a negative-energy one, so that, even if we suppose all the electrons in the world to be started off in positive-energy states, after a time some of them would be in negative-energy states.

Thus in allowing negative-energy states, the theory gives something which appears not to correspond to anything known experimentally, but which we cannot simply reject by a new assumption. We must find some meaning for these states.

An examination of the behaviour of these states in an electromagnetic field shows that they correspond to the motion of an electron with a positive charge instead of the usual negative one - what the experimenters now call a positron. One might, therefore, be inclined to assume that electrons in negative-energy states are just positrons, but this will not do, because the observed positrons certainly do not have negative energies. We can, however, establish ‘a connection between electrons in negative-energy states and positrons, in a rather more indirect way.

We make use of the exclusion principle of Pauli, according to which there can be only one electron in any state of motion. We now make the assumptions that in the world as we know it, nearly all the states of negative energy for the electrons are occupied, with just one electron in each state, and that a uniform filling of all the negative-energy states is completely unobservable to us. Further, *any unoccupied negative-energy state, being a departure from uniformity, is observable and is just a positron.*

An unoccupied negative-energy state, or *hole,* as we may call it for brevity, will have a positive energy, since it is a place where there is a shortage of negative energy. A hole is, in fact, just like an ordinary particle, and its identification with the positron seems the most reasonable way of getting over the difficulty of the appearance of negative energies in our equations. On this view the positron is just a mirror-image of the electron, having exactly the same mass and opposite charge. This has already been roughly confirmed by experiment. The positron should also have similar spin properties to the electron, but this has not yet been confirmed by experiment.

From our theoretical picture, we should expect an ordinary electron, with positive energy, to be able to drop into a hole and fill up this hole, the energy being liberated in the form of electromagnetic radiation. This would mean a process in which an electron and a positron annihilate one another. The converse process, namely the creation of an electron and a positron from electromagnetic radiation, should also be able to take place. Such processes appear to have been found experimentally, and are at present being more closely investigated by experimenters.

The theory of electrons and positrons which I have just outlined is a self-consistent theory which fits the experimental facts so far as is yet known. One would like to have an equally satisfactory theory for protons. One might perhaps think that the same theory could be applied to protons. This would require the possibility of existence of negatively charged protons forming a mirror-image of the usual positively charged ones. There is, however, some recent experimental evidence obtained by Stern about the spin magnetic moment of the proton, which conflicts with this theory for the proton. As the proton is so much heavier than the electron, it is quite likely that it requires some more complicated theory, though one cannot at the present time say what this theory is.

In any case I think it is probable that negative protons can exist, since as far as the theory is yet definite, there is a complete and perfect symmetry between positive and negative electric charge, and if this symmetry is really fundamental in nature, it must be possible to reverse the charge on any kind of particle. The negative protons would of course be much harder to produce experimentally, since a much larger energy would be required, corresponding to the larger mass.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Biography

Paul Adrien Maurice Dirac was born on 8th August, 1902, at Bristol, England, his father being Swiss and his mother English. He was educated at the Merchant Venturer's Secondary School, Bristol, then went on to Bristol University. Here, he studied electrical engineering, obtaining the B.Sc. (Engineering) degree in 1921. He then studied mathematics for two years at Bristol University, later going on to St. John's College, Cambridge, as a research student in mathematics. He received his Ph.D. degree in 1926. The following year he became a Fellow of St. John's College and, in 1932, Lucasian Professor of Mathematics at Cambridge.

Dirac's work has been concerned with the mathematical and theoretical aspects of quantum mechanics. He began work on the new quantum mechanics as soon as it was introduced by Heisenberg in 1925-independently producing a mathematical equivalent which consisted essentially of a non-commutative algebra for calculating atomic properties-and wrote a series of papers on the subject, published mainly in the Proceedings of the Royal Society, leading up to his relativistic *theory* of *the electron* (1928) and the *theory* of *holes* (1930). This latter theory required the existence of a positive particle having the same mass and charge as the known (negative) electron. This, the *positron* was discovered experimentally at a later date (1932) by C. D. Anderson, while its existence was likewise proved by Blackett and Occhialini(I933) in the phenomena of <<pair production>> and <<annihilation>>.

The importance of Dirac's work lies essentially in his famous wave equation, which introduced special relativity into Schrödinger's equation. Taking into account the fact that, mathematically speaking, relativity theory and quantum theory are not only distinct from each other, but also oppose each other, Dirac's work could be considered a fruitful reconciliation between the two theories.

Dirac's publications include the books *Quantum Theory of the Electron* (1928) and *The Principles of Quantum Mechanics* (1930; 3rd ed. 1947).

He was elected a Fellow of the Royal Society in 1930, being awarded the

Society's Royal Medal and the Copley Medal. He was elected a member of the Pontifical Academy of Sciences in 1961.

Dirac has travelled extensively and studied at various foreign universities, including Copenhagen, Göttingen, Leyden,Wisconsin, Michigan, and Princeton (in 1934, as Visiting Professor). In 1929, after having Spent five months in America, he went round the world, visiting Japan together with Heisenberg, and then returned across Siberia.

In 1937 he married Margit Wigner, of Budapest.

Physics 1934

Prize not awarded.

Physics **1935**

JAMES CHADWICK

<<for his discovery of the neutron>>

Physics 1935

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

This year like two years ago the Academy of Sciences awards the Nobel Prize for Physics as a reward for discoveries in the world of atoms and molecules. However, a fundamental difference is to be observed between the prizewinners of this year and the prizes that were awarded last time. The latter formed the reward for investigations of more theoretical nature, viz. the discovery of laws regulating the great many phenomena having been brought into light by experimental research. This year the Nobel Prize for Physics is awarded as a reward for a discovery, confirmed in an experimental way, of a new fundamental building-stone of atoms and molecules, viz. the discovery of the so-called *neutron*. By a combination of intuition, logical thought, and experimental research Professor J. Chadwick, the laureate of this year, has succeeded in proving the existence of the neutron and establishing its properties.

One of the Nobel Prize winners for the year 1933, Professor Heisenberg, had concluded by his researches that, owing to reasons of principle as well as to the roughness of our senses and our instruments, it would be impossible for us to arrive at an exact knowledge of what takes place within the atoms. However, experimental research has made undaunted progress, and by the aid of refined methods and new instruments today's Nobel Prize winners in Physics and Chemistry have succeeded in presenting science with a new and deeper knowledge of the structure and qualities of matter.

The Nobel Prize for Physics for this year is awarded as a reward for the discovery of the *neutron.*

The neutron is a heavy particle without any electric charge and of the same weight as the nucleus of an atom of hydrogen.

At the decomposition of the radioactive substances and at the disintegration of atoms and molecules two kinds of particles were always found. One of them that has been called *electron,* has an extremely small weight, amounting to about 1/2000 of the weight of an atom of hydrogen. The electron is charged with negative electricity, the quantity of the charge being always the same, in whatever way the electron may have appeared. The other kind of particles proved to have a weight of the same size as that of the atom of hydrogen, or a multiple of the same. This heavy particle is always combined with a charge of positive electricity, whose quantity turned out to be equal to or a multiple of the charge of the electron. The smallest particle with positive charge, found in this way, consists of the nucleus of the atom of hydrogen, and its positive charge equals the negative charge of the electron. This smallest, heavy particle with positive charge has received the name of *proton*. Owing to the disintegration of atoms always resulting in protons and electrons, the theory was established that the atoms were composed of protons and electrons. The atom was thought of as having the form of a planetary system where the central body consists of protons, combined to a nucleus; outside this nucleus the negative light electrons circle like the planets round the sun. The number of electrons is different with different substances. The lightest element, hydrogen, has only one electron, helium has two, etc.

That the atom may be in a neutral state of electricity, the positive charge of the nucleus must be the same as the total charge of the exterior electrons. The simplest relation would here have been that the number of protons in the nucleus had been the same as that of the electrons circling about the nucleus. This proved, however, not to be the case. In the atoms belonging to different elements it was found that, apart from hydrogen, the nucleus had about twice as many protons as the number of exterior electrons. Thus e.g. helium has the weight four in relation to the nucleus of hydrogen but only two exterior electrons. That the atom may be neutral in electric respect, the supposition is necessary that the surplus of positive electricity that the nucleus thus receives owing to the greater number of protons, was compensated by negative electrons also entering the nucleus. The nucleus of helium was thus supposed to consist of four protons and two electrons, and about this nucleus there circle two electrons.

At first this idea of the atom could be made to agree fairly well with experience. The nucleus-charge resulting determines the character of the atom and its place among the elements. The number of exterior electrons and the distribution of their paths at different distances from the nucleus are determinative of the physical and chemical qualities of the element; if one electron suddenly passes from one path to another, light is emitted, and if electrons from the paths closer to the nucleus are flung from the atom, X-rays are emitted, and so on. If the number of protons is increased or diminished in a nucleus, but the charge of the nucleus is still kept unaltered by the addition or the loss of negative electrons, the same element is still obtained but with different atomic weight; a so-called isotope is obtained. Thus e.g. lead is found in several different forms with different weight; and heavy hydrogen, the object of last year's Nobel Prize for Chemistry, is a similar modification of normal hydrogen.

A continued study of the conditions of energy at the disintegration of the nuclei of atoms showed, however, that the theory of the nuclei being composed of protons and electrons could scarcely be brought to agree with theoretical and experimental facts. As often happens in these spheres, it was the discovery of new phenomena, difficult to explain, that gave rise to the solution of the problem about the structure of the nuclei of atoms. In 1930 the scientists Bothe and Becker had found a new strange radiation that appeared, when the substance *beryllium* was bombarded with nuclei of helium. This new radiation, which was called *the radiation of beryllium* proved extremely penetrating. The rays could pierce a brass plate, several centimeters thick, without any noteworthy loss of velocity. When hitting nuclei of atoms, this new radiation caused a disintegration of them, similar to an explosion.

As a matter of course the new rays became at once the object of intensive experimental research, in which today's Nobel Prize winners in Chemistry, the couple Joliot, have taken an active and important part. At that time it was generally supposed that the radiation of beryllium was of the same nature as the electromagnetic waves of extremely short wavelength arising at the disintegration of radioactive substances. This radiation has received the name of γ-radiation and has the same qualities as the well-known X-rays. However, it was found that the new radiation possessed a power considerably superior to that of the strongest radioactive γ-rays; a correspondent radiation from another element, boron, proved, however, still stronger.

During their investigations of the radiation of beryllium, the couple Johot made the important observation that a block of paraffin or another substance containing hydrogen being bombarded with the new rays, will emit an intensive stream of protons. With the assistance of the expansion chamber, constructed by the Nobel Prize winner Wilson, in which the paths of particles with electric charge - protons or electrons - could be made visible, it was possible to calculate the energy of the protons emitted from paraffin and thus also that of the radiation of beryllium causing the stream of protons. Then it turned out that the values of energy obtained, if the radiation of beryllium was supposed to be a γ-radiation, became absurdly high. Nor could these values of energy be brought to agree with the energy to be reckoned with in the radiation giving rise to the radiation of beryllium.

Chadwick, who had undertaken investigations of the radiation of beryllium, found a similar radiation from quite a number of other elements, e.g. helium, lithium, carbon, nitrogen, and argon. By his extensive studies and calculations on conditions of energy at collisions, he was soon convinced that the radiation of beryllium could not be a γ-radiation.

Already in 1920 Lord Rutherford had suggested that, apart from protons and electrons, there also existed particles of the same weight as a proton but without any electric charge. To this particle was given in advance the name of *neutron.* This neutron had long been searched for but without any result. It is also easily understood how difficult it would be to discover this particle without electric charge. The neutron and the proton are certainly, like the electron, both particles of extremely small dimensions. But owing to their charges, the proton as well as the electron are accompanied by electric fields, which make them act as bodies of considerably larger dimensions, and their charges are influenced by the charges of the atoms they pass; these charged particles are therefore strongly checked when passing through substantial bodies. The neutron, on the contrary, having no electric charge is not affected and is not checked in its way, until it directly hits another particle, which happens extremely seldom owing to the small dimensions of the particles in relation to the distance between them. This explains why a neutron may pass through several kilometers of air, before losing its energy of motion. The motion of a proton or an electron may be observed in the above-mentioned Wilson chamber, and these particles being charged with electricity, their courses will be curved, if they are exposed to electric or magnetic fields. This curve may be studied in the Wilson chamber. The neutron, on the other hand, being without any charge, is not affected by such fields and may be discovered only in the case of a direct collision with the nucleus of an atom.

Chadwick now studied how, at a collision between radiation of beryllium and nuclei of atoms, the exchange of energy would be, supposing that the radiation of beryllium consisted of neutrons flung out from beryllium, and he then found that the experimental results attained agreed well with his own calculations. The same was the case also with radiation from other substances. By these facts the existence of the neutron was beyond all doubt. Chadwick then examined the exchange of mass taking place when by collision the nuclei of different substances are changed into new nuclei, belonging to other substances, and into neutrons. As an example may be mentioned that the nucleus of helium, when meeting that of beryllium, gives rise to a nucleus of carbon plus a neutron. Knowing the masses of different nuclei, it is possible directly to calculate the mass of the neutron. By examining the exchange of mass at a great number of collisions between the nuclei of different elements Chadwick succeeded in determining exactly the mass of the neutron, and as was to be expected, he found it almost the same as that of the proton or that of the nucleus of hydrogen.

On the other hand these researches have given a new method for the exact calculation of the size of masses in the nuclei of different elements. As characteristic for the usefulness of this new method may be mentioned that in this way Chadwick obtained another value for hydrogen than the earlier one observed by Aston with his spectrograph of mass. Aston, having improved his spectrograph, has obtained new values for the mass of hydrogen agreeing with those obtained by Chadwick.

The existence of the neutron having thus been proved, it was no more necessary to suppose compensatory charges of electron in the nuclei. The nucleus of atoms is nowadays considered to be composed of a number of protons and neutrons. Thus the nucleus of helium consists of two protons and two neutrons; about the nucleus there circle in the atom two electrons. Isotopes are formed by surplus or lack of the number of neutrons in the solid atom.

Owing to its weight and its great penetrating power, the neutron has become a powerful resource to bring about the disintegration of atoms and of nuclei of atoms, and during the last few years this power of the neutron to split up atoms and molecules has been largely made use of.

The existence of the neutron having been fully established, scientists have, as has just been mentioned, come to a new conception of the structure of atoms which agrees better with the distribution of energy within the nuclei of atoms. It has proved obvious that the neutron forms one of the building-stones of atoms and molecules and thus also of material universe.

However, there are still many questions to be answered, among others the one about the relations of protons and neutrons to each other. There are certain signs indicating that these two particles are modifications of one and the same primitive particle. The existence of the positive electron, found by Dirac by theoretical research, having now beenexperimentally proved, the task of physical science will be to examine, more closely, the relations existing between this electron and the parts of the nuclei of atoms - the proton and the neutron; the neutron discovered by Chadwick has here given a powerful instrument for future researches on the structure of atoms and molecules. If the qualities of the neutron are made use of, this will certainly in the immediate future give us a new and deeper knowledge of matter and its transformations.

Professor Chadwick. The Royal Academy of Sciences has awarded you the Nobel Prize for Physics for your discovery of the neutron.

We congratulate you to this most important result by which has been revealed a new building-stone of matter playing the same fundamental part as the proton and the electron.

By means of a new method, created by you, you have been able to determine the mass of the neutron, and by the same method you have found new, more exact values of the atomic weights of a number of elements.

In the neutron Science has obtained a powerful means of splitting up atoms and molecules which has already given important results.

I now ask you, Mr. Chadwick, to receive the prize from the hands of His Majesty.

JAMES CHADWICK

The neutron and its properties

Nobel Lecture, December 12, 1935

The idea that there might exist small particles with no electrical charge has been put forward several times. Nernst, for example, suggested that a neutral particle might be formed by a negative electron and an equal positive charge, and that these <<neutrons>> might possess many of the properties of the ether; while Bragg at one time suggested that the y-rays emitted by radioactive substances consisted of small neutral particles, which, on breaking up, released a negative electron.

The first suggestion of a neutral particle with the properties of the neutron we now know, was made by Rutherford in 1920. He thought that a proton and an electron might unite in a much more intimate way than they do in the hydrogen atom, and so form a particle of no nett charge and with a mass nearly the same as that of the hydrogen atom. His view was that with such a particle as the first step in the formation of atomic nuclei from the two elementary units in the structure of matter - the proton and the electron - it would be much easier to picture how heavy complex nuclei can be gradually built up from the simpler ones. He pointed out that this neutral particle would have peculiar and interesting properties. It may be of interest to quote his remarks :

<<Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field.

The existence of such atoms seems almost necessary to explain the building up of the nuclei of heavy elements; for unless we suppose the production of charged particles of very high velocities it is difficult to see how any positively charged particle can reach the nucleus of a heavy atom against its intense repulsive field.>>

Rutherford's conception of closely combined proton and electron was adopted in pictures of nuclear structure developed by Ono (1926), by Fournier and others, but nothing essentially new was added *to* it.

No experimental evidence for the existence of neutral particles could be obtained for years. Some experiments were made in the Cavendish Laboratory in 1921 by Glasson and by Roberts, hoping to detect the formation of such particles when an electric discharge was passed through hydrogen. Their results were negative.

The possibility that neutral particles might exist was, nevertheless, not lost sight of. I myself made several attempts to detect them - in discharge tubes actuated in different ways, in the disintegration of radioactive substances, and in artificial disintegrations produced by α-particles.* No doubt similar experiments were made in other laboratories, with the same result.

Later, Bothe and Becker showed that y-radiations were excited in some light elements when bombarded by a-particles. Mr. H. C. Webster, in the Cavendish Laboratory had also been making similar experiments, and he proceeded to examine closely the production of these radiations. The radiation emitted by beryllium showed some rather peculiar features, which were very difficult to explain. I suggested therefore that the radiation might consist of neutral particles and that a test of this hypothesis might be made by passing the radiation into an expansion chamber. Several photographs were taken: some p-particle tracks -presumably recoil electrons - were observed, but nothing unexpected.**

The first real step towards the discovery of the neutron was given by a very beautiful experiment of Mme. and M. Joliot-Curie, who were also investigating the properties of this beryllium radiation. They passed the radiation through a very thin window into an ionization vessel containing air. When paraffin wax or any other matter containing hydrogen was placed in front of the window the ionization in the vessel increased. They showed that this increase was due to the ejection from the wax of protons, moving with very high velocities.

This behaviour of the beryllium radiation was very difficult to explain if it were a quantum radiation. I therefore began immediately the study of this new effect using different methods - the counter, the expansion chamber, and the high-pressure ionization chamber.

It appeared at once that the beryllium radiation could eject particles not

* Cf. Rutherford and Chadwick, *Proc. Cambridge Phil. Soc.*, 25 (1929) 186.

** The failure was partly due to the weakness of the polonium source.

only from paraffin wax but also from other light substances, such as lithium, beryllium, boron, etc., though in these cases the particles had a range of only a few millimetres in air. The experiments showed that the particles are recoil atoms of the element through which the radiation passes, set in motion by the impact of the radiation.

The occurrence of these recoil atoms can be shown most strikingly by means of the expansion chamber. These experiments were carried out by Dr. Feather and Mr. Dee.

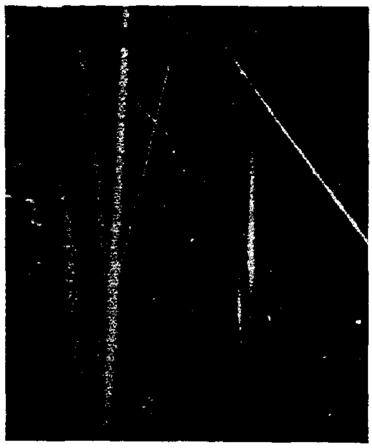

Fig. 1.

Fig. 1 is a photograph taken by Dee, which shows the tracks of protons ejected from gelatine on the roof of the expansion chamber. Fig. 2 shows two photographs taken by Feather, using an expansion chamber filled with nitrogen. Two short dense tracks are seen. Each is due to an atom of nitrogen which has been struck by the radiation. One track (Fig. 2b) shows a short spur, due to collision with a nitrogen atom; the angle between the spurs is 90°, as it should be if the initial track is due to a nitrogen atom.

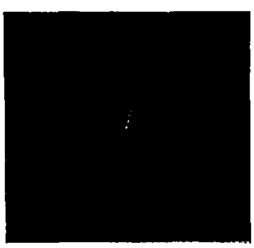

Fig. 2a.

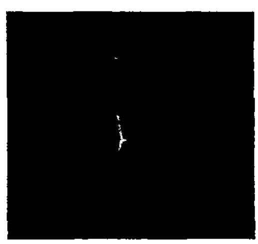

Fig. 2b.

The beryllium radiation thus behaved very differently from a quantum radiation. This property of setting in motion the atoms of matter in its path suggests that the radiation consists of particles.

Let us suppose that the radiation consists of particles of mass M moving with velocities up to a maximum velocity V. Then the maximum velocity which can be imparted to a hydrogen atom, mass 1, by the impart of such a particle will be

$$U_p = \frac{2M}{M+1} V$$

and the maximum velocity imparted to a nitrogen atom will be

$$U_n = \frac{2M}{M+14} V$$

Then

$$\frac{M+14}{M+1} = \frac{U_p}{U_n}$$

The velocities U_p and U_n were found by experiment. The maximum range of the protons ejected from paraffin wax was measured and also the ranges of the recoil atoms produced in an expansion chamber filled with nitrogen. From these ranges the velocities U_p and U_n can be deduced approximately: U_p = ca. 3.7 x 10^9 cm/sec, U_n = ca. 4.7 x 10^8 cm/sec. Thus we find M = 0.9.

We must conclude that the beryllium radiation does in fact consist of particles, and that these particles have a mass about the same as that of a proton. Now the experiments further showed that these particles can pass easily through thicknesses of matter, e.g. 10 or even 20 cm lead. But a proton of the same velocity as this particle is stopped by a thickness of $\frac{1}{4}$ mm of lead. Since the penetrating power of particles of the same mass and speed depends only on the charge carried by the particle, it was clear that the particle of the beryllium radiation must have a very small charge compared with that of the proton. It was simplest to assume that it has no charge at all. All the prop erties of the beryllium radiation could be readily explained on this assumption, that the radiation consists of particles of mass 1 and charge o, or neutrons.

The nature of the neutron

I have already mentioned Rutherford's suggestion that there might exist a neutral particle formed by the close combination of a proton and an electron, and it was at first natural to suppose that the neutron might be such a complex particle. On the other hand, a structure of this kind cannot be fitted into the scheme of the quantum mechanics, in which the hydrogen atom represents the only possible combination of a proton and an electron. Moreover, an argument derived from the spins of the particles is against this view. The statistics and spins of the lighter elements can only be given a consistent description if we assume that the neutron is an elementary particle.

Similar arguments make it difficult to suppose that the proton is a combination of neutron and positive electron. It seems at present useless to discuss whether the neutron and proton are elementary particles or not; it may be that they are two different states of the fundamental heavy particle.

In the present view of the γ-transformations of radioactive bodies the hypothesis is made that a neutron in the nucleus may transform into a proton and a negative electron with the emission of the electron, or conversely a proton in the nucleus may transform into a neutron and a positive electron with the emission of the positron. Thus

$$n \rightarrow p + e^-$$
$$p \rightarrow n + e^+$$

If spin is to be conserved in this process we must invoke the aid of another particle - Pauli's neutrino; we then write

$$n \rightarrow n + e^- + \text{neutrino}$$
$$p \rightarrow n + e^+ + \text{antineutrino}$$

where the neutrino is a particle of very small mass, no charge, and spin ½.

If we knew the masses of the neutron and proton accurately, these considerations would give the mass of the hypothetical neutrino.

As I have shown, observations of the momenta transferred in collisions of a neutron with atomic nuclei lead to a value of the mass of the neutron but the measurements cannot be made with precision. To obtain an accurate estimate of the neutron mass we must use the energy relations in a disintegration process in which a neutron is liberated from an atomic nucleus. The best estimate at present is obtained from the disintegration of the deuteron by the photoelectric effect of a y-ray

$$^{2}_{1}D + h\nu \rightarrow {}^{1}_{1}p + {}^{1}_{0}n$$

The energy of the protons liberated by a y-ray quantum of $h\nu = 2.62 \times 10^6$ eV has been measured recently by Feather, Bretscher, and myself. It is 180,000 eV. Thus the total kinetic energy set free is 360,000 eV, giving a binding energy of the deuteron of 2.26 x 106 eV. Using the value of the deuteron mass given by Oliphant, Kempton, and Rutherford, we then obtain a value for the mass of the neutron of I.0085*. The mass of the hydrogen atom is 1.0081. It would seem therefore that a free neutron should be unstable, i.e. it can change spontaneously into a proton + electron + neutrino, unless the neutrino has a mass of the order of the mass of an electron. On the other hand, an argument from the shape of the b- ray spectra suggests that the mass of the neutrino is zero. One must await more exact measurements of the masses of hydrogen and deuterium before speculating further on this matter.

Passage of neutrons through matter

The neutron in its passage through matter loses its energy in collisions with the atomic nuclei and not with the electrons. The experiments of Dee showed that the primary ionization along the track of a neutron in air could not be as much as I ion pair in 3 metres' path, while Massey has calculated that it may be as low as I ion pair in 105 km. This behaviour is very different from that of a charged particle, such as a proton, which dissipates its energy almost entirely in electron collisions. The collision of a neutron with an atomic nucleus, although much more frequent than with an electron, is also a rare event, for the forces between a neutron and a nucleus are very small except at distances of the order of 10^{-12} cm. In a close collision the neutron may be deflected from its path and the struck nucleus may acquire sufficient energy to produce ions. The recoiling nucleus can then be detected either in an ionization chamber or by its track in an expansion chamber. In some of these collisions, however, the neutron enters the nucleus and a distintegration is

* Recent measurements of the mass of deuterium lead to a value of 1.0090 for the mass of the neutron.

produced. Such disintegrations were first observed by Feather in his observations on the passage of neutrons through an expansion chamber filled with nitrogen. An example is shown in Fig. 3. The disintegration process is

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{11}_{5}B + ^{4}_{2}He$$

Since these early experiments many examples of this type of disintegration have been observed by different workers.

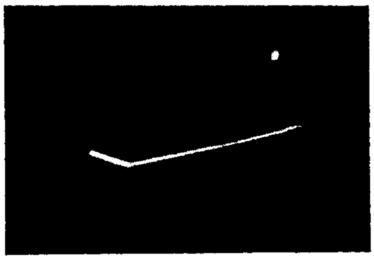

Fig.3.

Fermi and his collaborators have also shown that the phenomenon of artificial radioactivity can be provoked in the great majority of all elements, even in those of large atomic number, by the bombardment of neutrons. They have also shown that neutrons of very small kinetic energy are peculiarly effective in many cases.

In some cases an α-particle is emitted in the disintegration process; in others a proton is emitted; while in others an unstable species of nucleus is formed by the simple capture of the neutron.

Examples of these types are:

$$^{31}_{15}P + ^{1}_{0}n \rightarrow ^{28}_{13}Al + ^{4}_{2}He$$
$$^{28}_{14}Si + ^{1}_{0}n \rightarrow ^{28}_{13}Al + ^{1}_{1}H$$
$$^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{28}_{13}Al$$
$$^{127}_{53}I + ^{1}_{0}n \rightarrow ^{128}_{53}I$$

In the cases just cited the nuclei formed in the reaction are unstable, showing the phenomenon of induced activity discovered by Mme. and M. Joliot-Curie, and return to a stable form with the emission of negative electrons.

In the transformations produced in heavy elements by neutrons, the process is, with very few exceptions, one of simple capture. The nucleus so formed, an isotope of the original nucleus, is often unstable but not invariably so. For example the reaction

$$_{48}Cd + _{0}n \rightarrow _{48}Cd + h\nu$$

The cadmium isotope formed is stable, but a γ-ray quantum is emitted of energy corresponding to the binding energy of the neutron.

Other cases of this type of transformation are known.

The great effectiveness of the neutron in producing nuclear transmutations is not difficult to explain. In the collisions of a charged particle with a nucleus, the chance of entry is limited by the Coulomb forces between the particle and the nucleus; these impose a minimum distance of approach which increases with the atomic number of the nucleus and soon becomes so large that the chance of the particle entering the nucleus is very small. In the case of collisions of a neutron with a nucleus there is no limitation of this kind. The force between a neutron and a nucleus is inappreciable except at very small distances, when it increases very rapidly and is attractive. Instead of the potential wall in the case of the charged particle, the neutron encounters a potential hole. Thus even neutrons of very small energy can penetrate into a nucleus. Indeed slow neutrons may be enormously more effective than fast neutrons, for they spend a longer time in the nucleus. The calculations of Bethe show that the chance of capture of a neutron may be inversely proportional to its velocity. The possibility of capture will depend on whether the nucleus possesses an unoccupied p-level or a level with azimuthal quantum number $l = 1$.

In cases where a particle (α-particle or proton) is ejected from the nucleus, the possibility of disintegration will depend on whether the particle can escape through the potential barrier. This will be easier the greater the energy set free in the disintegration process. As a rule disintegration by neutrons will take place with absorption of kinetic energy if a proton is released in the transformation, and may take place with release of kinetic energy if one at least of the products is an α-particle. Thus processes in which a proton is emitted can only occur with fast neutrons, even in collisions with elements of low atomic number; while processes in which a-particles are emitted can occur with slow neutrons in elements of low atomic number, but again only with fast neutrons in elements of higher atomic number. If the atomic number is sufficiently high, the neutrons at present at our disposal have insufficient energy and the particles cannot escape through the potential barrier. Thus with elements of high atomic number, only capture processes are observed, although there may be a few exceptions. There may be, however, special cases in which the particles escape through a resonance level. These would be characterized by the phenomenon that the energy of the escaping particle would be independent of the energy of the incident neutron. These special cases may explain the exceptional disintegrations in which a particle is emitted from a heavy nucleus. They may be of particular interest in giving information about the resonance levels of atomic nuclei.

There is also the possibility of resonance capture of the neutrons, more particularly with very slow neutrons. The capture of neutrons of a certain energy may take place with very great frequency in one species of nucleus while for another neighbouring nucleus the same neutrons may have a long free path. These resonance regions may perhaps be rather broad and therefore comparatively easy to observe experimentally.

The structure of the nucleus

Before the discovery of the neutron we had to assume that the fundamental particles from which an atomic nucleus was built up were the proton and the electron, with the α-particle as a secondary unit. The behaviour of an electron in a space of nuclear dimensions cannot be described on present theory; and other difficulties, e.g. the statistics of the nitrogen nucleus, the peculiarities in the mass defect curve in the region of the heavy elements, also arose. These difficulties are removed if we suppose that the nuclei are built up from protons and neutrons. The forces which determine the stability of a nucleus will then be of three types, the interactions between proton and proton, between proton and neutron, and between neutron and neutron. It is assumed, with Heisenberg and Majorana, that the interaction between neutron and proton is of the exchange type - similar to that between the hydrogen atom and the hydrogen ion - and that the interaction between neutron and neutron is small.

For a nucleus of mass number A and charge Ze we shall have

$$N_n + N_p = A \qquad N_p = Z$$
$$N_n/N_p = (A-Z)/Z$$

The value of N_n/N_p for the most stable nucleus of a given mass number will be determined by the condition that the binding energy is a maximum. The repulsive Coulomb force between the protons tends to diminish the number of protons in a nucleus, while the neutron-proton interaction tends to make $N_n = N_p$, Z = $A/2$; the neutron-neutron interaction is probably very small. Now in existing nuclei $N_p \sim N_n$, and therefore the neutron-proton interaction must be the predominating force in the nucleus. In heavy elements $N_n > N_p$. This relative increase in the number of neutrons may be due either to an attractive force between neutron-neutron, or more probably to the Coulomb forces between proton-proton.

Thus it appears that the interaction between proton and neutron is of the highest significance in nuclear structure and governs the stability of a nucleus. It is most important to obtain all experimental evidence about the nature of this interaction. The information we have at present is very meagre, but I think that it does to some degree support the view that the interaction is of the exchange type. Dr. Feather and I hope to obtain more definite information on this subject by an extensive study of the collisions of neutrons and protons.

Heisenberg's considerations of nuclear structure point very strongly to this exchange interaction. Such an interaction provides an attractive force at large distances between the particles and a repulsive force at very small distances, thus giving the effect of a more or less definite radius of the particles. A system of particles interacting with exchange forces will keep together due to the attraction, but there will be a minimum distance of approach of the particles; thus the system will not collapse together but will have a more or less definite <<radius>>

The exchange forces between a hydrogen atom and a hydrogen ion are large compared with the forces between neutral atoms; by analogy we explain why the neutron-proton interaction is so much stronger than the proton-proton or neutron-neutron interactions.

By a suitable choice of the exchange forces it is possible to obtain a saturation effect, analogous to the saturation of valency bindings between two atoms, when each neutron is bound to two protons and each proton to two neutrons. Thus two neutrons and two protons form a closed system - the α-particle.

These ideas thus explain the general features of the structure of atomic nuclei and it can be confidently expected that further work on these lines may reveal the elementary laws which govern the structure of matter.

Biography

James Chadwick was born in Cheshire, England, on 20th October, 1891, the son of John Joseph Chadwick and Anne Mary Knowles. He attended Manchester High School prior to entering Manchester University in 1908; he graduated from the Honours School of Physics in 1911 and spent the next two years under Professor (later Lord) Rutherford in the Physical Laboratory in Manchester, where he worked on various radioactivity problems, gaining his M.Sc. degree in 1913. That same year he was awarded the 1851 Exhibition Scholarship and proceeded to Berlin to work in the Physikalisch-Technische Reichsanstalt at Charlottenburg under Professor H. Geiger.

During World War I, he was interned in the Zivilgefangenenlager, Ruhleben. After the war, in 1919, he returned to England to accept the Wollaston Studentship at Gonville and Caius College, Cambridge, and to resume work under Rutherford, who in the meantime had moved to the Cavendish Laboratory, Cambridge. Rutherford had succeeded that year in disintegrating atoms by bombarding nitrogen with alpha particles, with the emission of a proton. This was the first artificial nuclear transformation. In Cambridge, Chadwick joined Rutherford in accomplishing the transmutation of other light elements by bombardment with alpha particles, and in making studies of the properties and structure of atomic nuclei.

He was elected Fellow of Gonville and Caius College (1921-1935) and became Assistant Director of Research in the Cavendish Laboratory (1923-1935). In 1927 he was elected a Fellow of the Royal Society.

In 1932, Chadwick made a fundamental discovery in the domain of nuclear science: he proved the existence of *neutrons*- elementary particles devoid of any electrical charge. In contrast with the helium nuclei (alpha rays) which are charged, and therefore repelled by the considerable electrical forces present in the nuclei of heavy atoms, this new tool in atomic disintegration need not overcome any electric barrier and is capable of penetrating and splitting the nuclei of even the heaviest elements. Chadwick in this way prepared the way towards the fission of uranium 235 and towards the creation of the atomic bomb. For this epoch-making discovery he was awarded the Hughes Medal of the Royal Society in 1932, and subsequently the Nobel Prize for Physics in 1935.

He remained at Cambridge until 1935 when he was elected to the Lyon Jones Chair of Physics in the University of Liverpool. From 1943 to 1946 he worked in the United States as Head of the British Mission attached to the Manhattan Project for the development of the atomic bomb. He returned to England and, in 1948, retired from active physics and his position at Liverpool on his election as Master of Gonville and Caius College, Cambridge. He retired from this Mastership in 1959. From 1957 to 1962 he was a part-time member of the United Kingdom Atomic Energy Authority.

Chadwick has had many papers published on the topic of radioactivity and connected problems and, with Lord Rutherford and C. D. Ellis, he is co-author of the book *Radiations from Radioactive substances* (1930).

Sir James was knighted in 1945. Apart from the Hughes Medal (Royal Society) mentioned above, he received the Copley Medal (1950) and the Franklin Medal of the Franklin Institute, Philadelphia (1951). He is an Honorary Fellow of the Institute of Physics and, in addition to receiving honorary doctorate degrees from the Universities of Reading, Dublin, Leeds, Oxford, Birmingham, Montreal (McGill), Liverpool, and Edinburgh, he is a member of several foreign academies, being Associé of the Académie Royale de Belgique; Foreign Member of the Kongelige Danske Videnskabemes Selskab and the Koninklijke Nederlandse Akademie van Wetenschappen; Corresponding Member of the Sächsische Akademie der Wissenschaften, Leipzig ; Member of the Pontificia Academia Scientiarum and the Franklin Institute ; Honorary Member of the American Philosophical Society and the American Physical Society.

In 1925, he married Aileen Stewart-Brown of Liverpool. They have twin daughters, and live at Denbigh, NorthWales. His hobbies include gardening and fishing.

Physics 1936

VICTOR FRANZ HESS

<<for his discovery of cosmic radiation>>

CARL DAVID ANDERSON

<<for his discovery of the positron>>

Physics 1936

Presentation Speech by Prof. H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The year 1895 is a turning-point in the history of physics: Röntgen discovered the rays that were to be called after him, and this was rapidly followed by Becquerel's discovery of radioactive radiation, and by the discovery of the negative electron - one of the fundamental elements of atomic structure.

Many research workers have made the radioactive rays discovered by Becquerel the subject of their investigations, starting with the Curies, husband and wife, who discovered the substance radium; these investigations have now come to a natural termination in the discovery by the Joliot-Curies, that normal atoms can be made radioactive by external influences.

The existence of a new, peculiar type of radiation, i.e. cosmic radiation, for the discovery of which Professor Victor Hess will today receive the Nobel Prize for Physics, became manifest during the search for sources of radioactive radiation. A few words on the nature of radioactive radiation may not come amiss. This radiation occurs during the explosion within the atomic nuclei of certain substances of instable structure. As is general knowledge, the rays derive their name from one of these substances, i.e. radium. In the event of an explosion in the atom, parts of the atom are ejected in all directions. The resulting rays are therefore bound to contain heavy, positively charged parts of the nucleus of the atom, and extremely light, negatively charged electrons on the periphery of the atom. When the energy in the atom is liberated, there occurs, apart from these two types of rays, a strong radiation, the so-called gamma rays, which are of the same nature as X-rays. During this explosion of the atom, other elements are formed by it. One element is therefore changed into another. The presence of radioactive rays can be detected from the circumstance that the emitted rays split the molecules of the air into positive and negative components and render the circumambient air electrically conductive, i.e. ionize it. An instrument that is electrically charged, e.g. an electroscope, will therefore lose its electrical charge when it is surrounded by air exposed to radioactive radiation.

The instrument can on the other hand be protected against such radiation by being encased in lead plates of sufficient thickness.

During the years that followed the discovery of radioactive rays a search was made throughout nature for radioactive substances: in the crust of the earth, in the seas, and in the atmosphere; and the instrument just mentioned - the electroscope - was applied. Radioactive rays were found everywhere, whether investigations were made into the waters of deep lakes, or into high mountains. The most surprising discovery that was made was that it was impossible to eliminate the influence of the rays, no matter how thick were the lead plates that encased the instrument. This was inexplicable if the rays were to emanate from radioactive substance in the earth or from the atmosphere, and research workers were therefore compelled to the assumption that there exists another source of radiation unknown to us, with rays of immense powers of penetration.

In searching for this new source of radiation, it was obvious to investigate whether radiation decreased at high levels above the earth's surface. Such experiments were done by various research workers, including some on the Eiffel Tower. The experiments showed some decrease of radiation with increasing distance from the earth's surface, but not at the rate to be expected if radiation emanated from the earth. Observations were extended to greater heights by balloon ascents. In ascents to a height of 4,500 m a slight decrease with height was observed in some cases, but in other cases, ionization remained practically unchanged.

Although no definite results were gained from these investigations, they did show that the omnipresent radiation could not be attributed to radiation of radioactive substances in the earth's crust.

The mystery of the origin of this radiation remained unsolved until Prof. Hess made it his problem. Hess who was from the start of the opinion that the radiation was due to very powerful gamma rays, first investigated in detail the manner in which such rays are weakened on passing through dense layers of air. The sources of error in the instruments used were also investigated. With superb experimental skill Hess perfected the instrumental equipment used and eliminated its sources of error. With these preparations completed, Hess made a number of balloon ascents to heights up to 5,300 m, in 1911 and 1912. His systematic measurements showed that a decrease in ionization did occur up to 1,000 m, but that it increased considerably thereafter, so that at 5,000 m radiation was twice as intensive as on the earth's surface. Later ascents and investigations made by successors of Hess in free balloons equipped with recording instruments showed that at a height of 9,300 m radiation is about 40 times as intensive as on the earth's surface. From these investigations Hess drew the conclusion that there exists an extremely penetrating radiation coming from space which enters the earth's atmosphere. This radiation which has been found to come from all sides in space has been called cosmic radiation. Hess's investigations naturally aroused much interest and were received with much scepticism by many. No regular investigations into cosmic rays were carried out during the World War, but once war was over, investigations were resumed with enthusiasm both in Europe and in the USA, and before long the existence of cosmic radiation was generally accepted.

The new rays surpass in intensity and penetrating power everything previously known. They are capable of penetrating lead plates one metre thick and they have been detected on the floor of lakes with a depth of 500 m. The big question is: where does this radiation come from? During his first balloon ascents Hess observed that there was no particular difference between night and day, and no special influence either was detected in a balloon ascent during a solar eclipse. Cosmic radiation could not therefore originate in the sun.

At a later date Hess made extremely sensitive systematic measurements of the rays and found that they varied in one and the same place during the daily rotation of the earth with the position of the place relative to the fixed stars. The variation is small, only 0.1%. Meanwhile, Compton has shown theoretically that this change may be due to the motion of the sun and therefore of the earth in space. Being part of the galaxy, the solar system participates in the rotation of the galaxy, which imparts to the earth a velocity of about 300 km per second. The earth's motion results in an apparent increase in cosmic radiation, from the side towards which the earth moves, and in an apparent attenuation on the other side. Compton's calculations give the correct figure, from which the conclusion has been drawn that cosmic radiation does not come from our galaxy either, but from stellar systems far beyond it.

We still do not know what processes out in the deep fastnesses of space give rise to this radiation. Many theories have been put forward, but no one has yet been able to provide any detailed explanation of how these rays - over a thousand times more powerful than the strongest radioactivity - come into being. When in the years to come the mysteries thus posed by cosmic radiation have been completely or partially solved, this will surely shed new light on the interaction between energy and matter, and on the origin and disintegration of matter.

Professor Hess. By virtue of your purposeful researches into the effects of radioactive radiation carried out with exceptional experimental skill you discovered the surprising presence of radiation coming from the depths of space, i.e. cosmic radiation. As you have proved, this new radiation possesses a penetrating power and an intensity of previously unknown magnitude; it has become a powerful tool of research in physics, and has already given us important new results with respect to matter and its composition. The presence of this cosmic radiation has offered us new, important problems on the formation and destruction of matter, problems which open up new fields for research. We congratulate you on your fine achievements.

For your discovery of cosmic radiation, the Royal Academy of Sciences has awarded you the Nobel Prize for Physics, and I now call upon you, Professor Hess, to receive the award from the hands of His Majesty the King.

The experimental discovery of the positive electron, for which discovery Dr. Anderson receives today the Nobel Prize, has such an intimate relation to the cosmic radiation that I must take the liberty to touch once more upon this subject. After the existence of cosmic radiation had been clearly stated there arose the question of the nature of this radiation. On an earlier occasion this day I have had the opportunity of mentioning the various kinds of rays emanating from an atom of a radioactive substance, when this atom explodes. It has been stated that these rays consist partly of heavy, positively charged particles from the nucleus of the atom, partly of light, negative electrons, and finally of so-called gamma rays, which are of the same nature as X-rays and light rays although with an exceedingly short wavelength, and for this reason possessing great penetrating power. The two first kinds of rays, which consist of charged particles, have come to be called corpuscular rays. The question now arose, whether the cosmic radiation was a corpuscular radiation or whether it consisted of gamma rays. It was obvious, in order to settle this question, to examine the rays when passing between the poles of a powerful magnet. In the case that the rays consisted of charged particles, their paths would be changed by the magnetic field in different directions for various kinds of charge. If, on the other hand, they consisted of gamma rays, they would experience no influence from the magnetic field. An excellent instrument for the investigation of the nature of the rays is the Wilson chamber, which consists of a closed vessel filled with supersaturated steam. On account of the condensation caused by the passage of a ray, the path of the ray becomes visible to the eye and can be photographed. The first experiments carried out by means of a magnetic field showed, however, no deviation of the rays. But the high energy which the rays possess requires very strong magnetic fields to produce visible effects. Meanwhile investigations carried out along quite other lines had indicated the probability of the cosmic rays being corpuscular rays. The earth itself is a magnet and above all a big one. It has long been known that a corpuscular radiation consisting of negative electrons emanates from the sun. As Störmer has shown the rays are caused to deviate from the earth by its magnetic field. It is only at the magnetic poles, where the rays have the same direction as the magnetic force, that the rays can penetrate into the atmosphere of the earth, where they give rise to the phenomena called polar lights. On the other hand, the cosmic rays have a much greater penetrating power than the rays from the sun and therefore everywhere make their way down to the surface of the earth. It ought then to be expected that, owing to the influence of the magnetic field of the earth, a certain difference of the intensity of the radiation at the poles and at the equator should be noticeable. To demonstrate this Professor Clay in Amsterdam had, already in 1929, carried out comparative measurements of the cosmic radiation in Holland and Java, and these measurements have shown a distinct latitude effect. It might be mentioned, incidentally, that according to later investigation this effect increases considerably with increasing height above the earth. In order to be able to study more in detail the nature of cosmic radiation Millikan decided to set up, in his institute at Pasadena, an installation for experiments on a large scale containing, among other things, a Wilson chamber equipped with very strong magnets. The planning and direction of the experiments Millikan entrusted to Dr. Anderson. When some years later the installation was ready, the cosmic radiation was recorded day and night every 15 seconds. The result of the rich material thus collected was published in 1931. Upon examination of the photographs there were found, besides the curved paths of negative electrons, also paths deviating in the opposite direction, which accordingly should be attributed to positively charged particles. These paths could as a rule be interpreted as being traces of heavy nuclear residues. On one of the photographs, however, Dr. Anderson found a path with positive deviation, to which this interpretation was not applicable. Owing to their greater weight the nuclei maintain their rectilinear path better than the light electron. The peculiarity is that the path found by Dr. Anderson showed the same deviation as the negative electrons, but in the opposite direction. The most plausible interpretation was to suppose that this was the path of a positive electron with the same mass as the negative one. Previously Dirac had found by theoretical investigation that the equations which determine the electromagnetic field require the existence of such light positively charged particles of the same size as the negative electrons. Since, however, no such particles had been found Dirac formulated the hypothesis that it might be that in other parts of the universe positive and negative charge were reversed. Dr. Anderson now pursued his investigations, introduced certain improvements of the equipment and after having carried out verifying experiments and new measurements he was able to furnish, in the summer of 1932, clear evidence of the existence of the positive electron. The positron Dirac had been searching for was thus found. Now the traces of ray paths appearing in the Wilson chamber could either be due to the cosmic radiation itself or to secondary rays in the chamber or the walls of the chamber caused by rays which, coming from outside, had collided with atoms which were thereby split up into their constituents. It was therefore not yet possible to come to the conclusion that the cosmic rays in part or entirely consisted of charged particles. Several scientists and among them also Dr. Anderson found that the gamma radiation from a radioactive substance containing thorium could release, by interaction, positive as well as negative electrons. The peculiar thing is that then there is often formed a twin pair of electrons consisting of one positive and one negative electron. In this case particles are thus created by the influence of pure radiation energy. It has likewise been found that a positive and a negative particle disappear when united, the only trace left being radiation passing away in every direction.

During these later years an intensive scientific research programme has been carried out concerning the nature and qualities of cosmic radiation. To this work Dr. Anderson has made important contributions. Thus it has been shown that the cosmic radiation consists to a large extent of corpuscles which with enormous energy and velocity enter the atmosphere from all parts of the universe. Positive and negative electrons exist in this radiation in about the same quantities, but the positive electrons soon disappear after having entered the atmosphere, because they coalesce with the atoms. Dr. Anderson has studied the distribution of energy in the cosmic radiation and the loss of energy sustained when it passes through matter.

Doctor Anderson. In the course of your comprehensive studies on the nature and qualities of cosmic radiation you have made important and material contributions to the elucidation of the questions involved, and by utilizing ingenious devices you have succeeded in finding one of the building-stones of the universe, the positive electron. We congratulate you on this great success attained in your young years and we wish to express the hope that your further investigations will bring to science many new and equally important results.

For your discovery of the positron the Royal Swedish Academy of Sciences has awarded you the Nobel Prize in Physics, and I now request you to receive the prize from the hands of His Majesty.

VICTOR F. HESS

Unsolved problems in physics: tasks for the immediate future in cosmic ray studies

Nobel Lecture, December 12, 1936

From a consideration of the immense volume of newly discovered facts in the field of physics, especially atomic physics, in recent years it might well appear to the layman that the main problems were already solved and that only more detailed work was necessary.

This is far from the truth, as will be shown by one of the biggest and most important newly opened fields of research, with which I am closely associated, that of cosmic rays.

When, in 1912, I was able to demonstrate by means of a series of balloon ascents, that the ionization in a hermetically sealed vessel was reduced with increasing height from the earth (reduction in the effect of radioactive substances in the earth), but that it noticeably increased from 1,000 m onwards, and at 5 km height reached several times the observed value at earth level, I concluded that this ionization might be attributed to the penetration of the earth's atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity, which was still able to ionize the air at the earth's surface noticeably. Already at that time I sought to clarify the origin of this radiation, for which purpose I undertook a balloon ascent at the time of a nearly complete solar eclipse on the 12th April 1912, and took measurements at heights of two to three kilometres. As I was able to observe no reduction in ionization during the eclipse I decided that, essentially, the sun could not be the source of cosmic rays, at least as far as undeflected rays were concerned.

Many esteemed physicists in Europe and America have tried since then to solve the problems of the origin of cosmic rays. The fluctuations of intensity of the radiation already incidentally observed by me in 1912 have been thoroughly studied using apparatuses which have been constantly improved and perfected. An influence from specific sky zones which individual research workers (1923-1927) believed they had found, could not be confirmed later.

In the autumn of 1931 a small observatory for the continuous recording of the fluctuations in intensity of the cosmic rays was set up by me on a

2,300 m high mountain, the Hafelekar at Innsbruck in Austria. A great number of results are already available from there which will only be mentioned here briefly. The determination of a small, regular, daily fluctuation of radiation according to solar time (maximum at midday), which were attributed to atmospheric influences, particularly electrical and magnetic effects in the highest layers of the atmosphere. Further indications of a still smaller fluctuation according to stellar time, which would speak in favour of Prof. A. H. Compton's hypothesis published a year ago, according to which the cosmic rays come from milky-way systems external to, and far-distant from, our own. Further, evidence of simultaneous radiation fluctuations from day to day at two measuring devices spaced at 6 km from each other at heights of 600 and 2,300 m (fitted with ionization chambers, as well as with counting tubes).

On what can we now place our hopes of solving the many riddles which still exist as to the origin and composition of cosmic rays? It must be emphasized here above all that to attain really decisive progress greater funds must be made available. The further improvement of the method of sending up automatically recording instruments to heights above 25 km using pilot balloons, so successfully employed by Prof. Regener (Stuttgart), must be still further expanded and perfected. In conjunction, the many trial methods of automatic radiotelegraphic transmission of observation data as used in America for stratospheric flights will serve a useful purpose. It may well be said that the answer to the question: Of what do the cosmic rays in fact consist before they produce their familiar secondary radiation phenomena in the earth's atmosphere? can only be obtained from numerous measurements in the stratosphere. In conjunction with this, the study of the occurrence of the so-called showers and Hoffmann's bursts (release of enormous quantities of ions resulting from atomic disintegration processes) of cosmic rays at various heights will provide new knowledge about the effects of these rays.

In addition, the tracing of the occurrence of these <<showers>> in the depths of the earth, in mines and through the immersion of recording apparatus in water to some hundreds of metres depth will yield very important results.

In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side; an effort which has not yet been made, or at least, only to a limited extent. Simultaneous recording with superimposed ionization chambers and Wilson chambers, ionization chambers and sets of counting tubes, has not yet been carried out. The photographic method of observing the tracks of the particles of cosmic radiation, first succesfully tried out by Prof. Wilkins (Rochester, USA) merits great attention. The application of a strong magnetic field enables the measurement of the energy of the most penetrating particles to be carried out, and the method may be capable of still further extension and improvement.

The investigation into the possible effects of cosmic rays on living organisms will also offer great interest.

The investigation of the tracks of cosmic rays in strong magnetic fields by means of the Wilson cloud chamber method has led to the discovery of the positron (positively charged electrons), that is, one of the hitherto unknown fundamental components of matter; this was carried out by Prof. Carl Anderson (Pasadena) who was in 1936 awarded the Nobel Prize for this work, at the same time as I myself received the award.

It is likely that further research into <<showers>> and <<bursts>> of the cosmic rays may possibly lead to the discovery of still more elementary particles, neutrinos and negative protons, of which the existence has been postulated by some theoretical physicists in recent years.

Biography

Victor Franz Hess was born on the 24th of June, 1883, in Waldstein Castle, near Peggau in Steiermark, Austria. His father, Vinzens Hess, was a forester in Prince Öttingen-Wallerstein's service and his mother was Serafine Edle von Grossbauer-Waldstatt.

He received his entire education in Graz: Gymnasium (1893-1901), and afterwards Graz University (1901-1905), where he took his doctor's degree in 1910.

He worked, for a short time, at the Physical Institute in Vienna, where Professor von Schweidler initiated him in recent discoveries in the field of radioactivity. During 1910-1920 he was Assistant under Stephan Meyer at the Institute of Radium Research of the Viennese Academy of Sciences. In 1919 he received the Lieben Prize for his discovery of the <<ultra-radiation>> (cosmic radiation), and the year after became Extraordinary Professor of Experimental Physics at the Graz University.

From 1921 to 1923, Hess was granted leave of absence, and worked in the United States, where he took a post as Director of the Research Laboratory (created by him) of the U.S. Radium Corporation, at Orange (New Jersey), and as Consulting Physicist for the U.S. Department of the Interior (Bureau of Mines), Washington D.C.

In 1923 he returned to Graz University and in 1925 he was appointed Ordinary Professor of Experimental Physics. In 1931 came his appointment as Professor at Innsbruck University and Director of the newly established Institute of Radiology. He founded the station at the Hafelekar mountain (2,300 m) near Innsbruck for observing and studying cosmic rays.

As well as the Nobel Prize for 1936, which he shared with C. D. Anderson, Hess has been awarded the Abbe Memorial Prize and the Abbe Medal of the Carl Zeiss Institute in Jena (1932); he was also Corresponding Member of the Academy of Sciences in Vienna.

Hess's work. which gained him the Nobel Prize, was carried out during the years 1911 - 1913, and published in the Proceedings of the Viennese Academy of Sciences. In addition he has published some sixty papers and several books, of which the most important were : <<Die Wärmeproduktion des Radiums>> (The heat production of radium), 1912; <<Konvektionserscheinungen in ionisierten Gasen-Ionenwind>> (Convection phenomena in ionized gas-ionwinds), 1919-1920; <<The measurement of gamma rays>>, 1916 (with R. W. Lawson); <<The counting of alpha particles emitted from radium>>, 1918 (also with R. W. Lawson) *; Elektrische Leitfähigkeit der Atmosphäre und ihre Ursachen* (book), 1926 (in English: *The Electrical Conductivity of the Atmosphere and Its Causes*, 1928) *; Ionenbilanz der Atmosphäre* (The ionization balance of the atmosphere-book), 1933; *Luftlektrizität* (Electricity of the air-book, with H. Benndorf), 1928; <<Lebensdauer der Ionen in der Atmosphä>> (Average life of the ions in the atmosphere), 1927-1928; <<Schwankungen der Intensität in den kosmischen Strahlen>> (Intensity fluctuations in cosmic rays), 1929-1936.

Hess has been American citizen since 1944, and is living in New York.

CARL D. ANDERSON

The production and properties of positrons

Nobel Lecture, December 12, 1936

Information of fundamental importance to the general problem of atomic structure has resulted from systematic studies of the cosmic radiation carried out by the Wilson cloud-chamber method.

After Skobelzyn in 1927 had first shown photographs of tracks of cosmic-ray particles, Professor R. A. Millikan and the writer in the spring of 1930 planned a cloud-chamber apparatus suitable for cosmic-ray studies, in particular to measure the energies of cosmic-ray particles by means of their curvatures in a strong magnetic field. The chamber, of dimensions 17 x 17 x 3 cm, was arranged with its long dimension vertical, and incorporated into a powerful electromagnet capable of maintaining a uniform magnetic field up to 24,000 gauss strength.

In the summer of 1931 the first results were obtained with this technique. The direct measurement of the energies of atomic particles was extended from about 15 million electron-volts, the highest energy measured before that time, to 5 billion electron-volts. In the spring of 1932 a preliminary paper on the energies of cosmic-ray particles was published in which energies over 1 billion electron-volts were reported. It was here shown that particles of positive charge occurred about as abundantly as did those of negative charge, and in many cases several positive and negative particles were found to be projected simultaneously from a single center. The presence of positively charged particles and the occurrence of <<showers>> of several particles showed clearly that the absorption of cosmic rays in material substances is due primarily to a nuclear phenomenon of a new type.

Measurements of the specific ionization of both the positive and negative particles, by counting the number of droplets per unit length along the tracks, showed the great majority of both the positive and negative particles to possess unit electric charge. The particles of negative charge were readily interpreted as electrons, and those of positive charge were at first tentatively interpreted as protons, at that time the only known particle of unit positive charge.

If the particles of positive charge were to be ascribed to protons then those of low energy and sharp curvature in the magnetic field, (e.g. a curvature greater than that corresponding to an electron having an energy of about 500 million electron-volts), should be expected to exhibit an appreciably greater ionization than the negatively charged electrons. In general, however, the positive particles seemed to differ in specific ionization only inappreciably from the negative ones. To avoid the assumption, which appeared very radical at that time, that the positive particles had electronic mass, serious consideration was given to the possibility that the particles which appeared to be positively charged and directed downward into the earth were in reality negatively charged electrons which through scattering had suffered a reversal of direction and were projected upwards away from the earth. Although such a reversal of direction through scattering might be expected to occur occasionally it seemed inadequate to account for the large number of particle tracks which showed a specific ionization anomalously small if they were to be ascribed to protons.

To differentiate with certainty between the particles of positive and negative charge it was necessary only to determine without ambiguity their direction of motion. To accomplish this purpose a plate of lead was inserted across a horizontal diameter of the chamber. The direction of motion of the particles could then be readily ascertained due to the lower energy and therefore the smaller radius of curvature of the particles in the magnetic field after they had traversed the plate and suffered a loss in energy.

Results were then obtained which could logically be interpreted only in terms of particles of a positive charge and a mass of the same order of magnitude as that normally possessed by the free negative electron. In particular one photograph (see Fig. 1) shows a particle of positive charge traversing a 6 mm plate of lead. If electronic mass is assigned to this particle its energy before it traverses the plate is 63 million electron-volts and after it emerges its energy is 23 million electron-volts. The possibility that this partitle of positive charge could represent a proton is ruled out on the basis of range and curvature. A proton of the curvature shown after it emerges from the plate would have an energy of 200,000 electron-volts, and according to previously well-established experimental data would have a range of only 5 mm whereas the observed range was greater than 50 mm. The only possible conclusion seemed to be that this track, indeed, was the track of a positively charged electron. Examples similar to this and others in which two or more particles were found to be produced at one center gave additional evidence for the existence of particles of positive charge and mass,

Fig. 1. A 63 million electron-volt positron passing through a 6 mm lead plate and emerging with an energy of 23 million electron-volts. The length of this latter path is at least ten times greater than the possible length of a proton track of this curvature. (Magnetic field 15,000 gauss.) *In all the photographs the magnetic field is directed into the paper.*

small compared with that of the proton. These results formed the basis of the paper published in September 1932 announcing the existence of free positive electrons.

Measurements by the droplet counting method of the magnitude of the specific ionization of the positive and negative electrons which occur with energies low enough to be appreciably curved in the magnetic field have shown that the mass and charge of the positive electron cannot differ by more than 20 percent and 10 percent, respectively, from the mass and charge of the negative electron.

Blackett and Occhialini using an apparatus similar to ours but with the added advantage that through the use of control by Geiger-Müller tube counters their apparatus was made to respond automatically to the passage of a cosmic-ray particle, in the spring of 1933 confirmed the existence of positive electrons, or positrons, and obtained many beautiful photographs of complex electron showers.

That positrons could be produced by an agent other than cosmic rays was first shown by Chadwick, Blackett and Occhialini when they observed that positrons were produced by the radiation generated in the impact of alpha particles upon beryllium. The radiation produced in the beryllium is complex in character, consisting both of neutrons and gamma rays. In their experiment it was not possible to determine which of these rays was responsible for the production of positrons. Curie and Joliot by a similar experiment, in which they interposed blocks of lead and paraffin into the path of the rays from beryllium and measured the yield of positrons as a function of the thickness and material of the absorber concluded that the positrons arose more likely as a result of the gamma rays than of the neutrons.

Direct proof that the hard component of the gamma rays from ThC" can give rise to positrons was first given by Neddermeyer and the writer, and independently by Curie and Joliot, and by Meitner and Philipp in the spring of 1933. In Figs. 2 and 3 positrons produced by gamma rays from ThC" are shown.

In addition to the methods of producing positrons already mentioned, i.e. by absorption of cosmic-ray photons and electrons, and by the absorption of sufficiently high energy gamma rays from terrestrial sources, positrons have also been observed among the disintegration products of certain radioactive substances. The artificially produced radioactive elements first discovered by Curie and Joliot in 1934 are found to distintegrate either by the ejection of a positive or negative electron. Those elements whose atomic number is greater than that of the stable elements of the same mass number in general distintegrate by the ejection of a positron. Fig. 4 shows positrons resulting from the disintegration of $^{11}_{6}C$ prepared by bombarding a boron target with deuterons.

Theoretical interpretation

The present electron theory of Dirac provides a means of describing many of the phenomena governing the production and annihilation of positrons. Blackett and Occhialini first suggested that the appearance of pairs of positive and negative electrons could be understood in terms of this theory as the <<creation>> of a positive-negative electron pair in the neighborhood of an atomic nucleus. The energy corresponding to the proper mass of both of the particles, as well as to their kinetic energies, is, according to this view, sup-

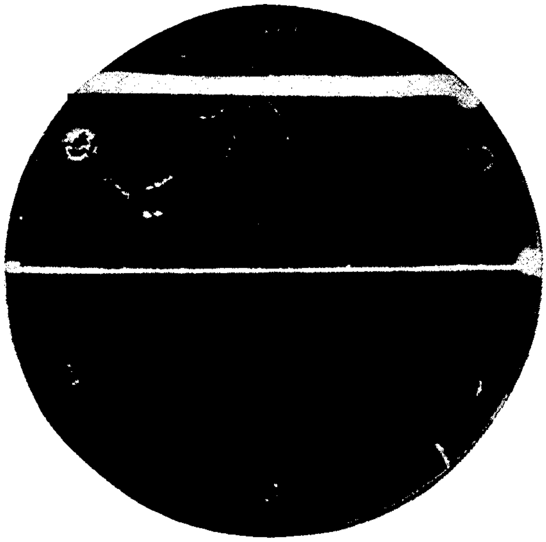

Fig. 2. A positron of 0.82 million electron-volts ejected from a lead plate by gamma rays from ThC" passes through a 0.5 mm aluminium plate and emerges with an energy of 0.52 million electron-volts. (Magnetic field 430 gauss.)

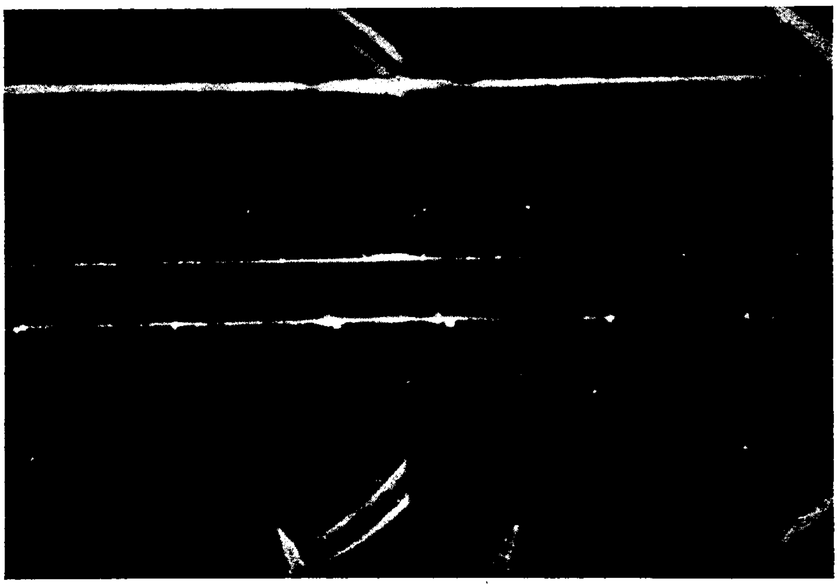

Fig. 3. A positive-negative electron pair produced in a lead plate by the gamma rays from ThC". (Magnetic field 800 gauss.) In this and *the remaining photographs the direct image is at the left; the right-hand reversed image is taken for stereoscopic observation.*

Fig. 4. Positrons produced in the distintegration of radioactive carbon of mass eleven units. (Magnetic field 780 gauss.) (The radioactive carbon was kindly supplied by Professor C. C. Lauritsen and his collaborators who prepared it by bombarding with deuterons a target containing boron.)

plied by the incident radiation. Since the energy corresponding to the proper mass of a pair of electrons is approximately one million electron-volts one should expect gamma rays of energy greater than this amount to produce positrons in their passage through matter, and further that the sum of the kinetic energies of the positive and negative electrons should be equal to the energy of the radiation producing them diminished by approximately one million electron-volts.

Experiments by Neddermeyer and the writer, and by Chadwick, Blackett and Occhialini, and others, have shown this relation to obtain in the production of positrons by ThC” gamma rays, providing evidence for the correctness of this view of the origin of positive-negative electron pairs.

The theory of Dirac requires further that a positron, when it finds itself in a very ordinary environment, as, for example, in passing through common substances, will, on the average, have only a very short life, of the order of one billionth of a second or less. The positrons and negative electrons will mutually annihilate one another in pairs, and in their stead will appear a pair of photons, each of approximately one-half million electron-volts energy.

Although the lifetime of positrons has not been actually measured, it has been shown to be very short, and the radiation which results from their annihilation has been observed. The first to do this were Joliot and Thibaud. The annihilation radiation is of the proper intensity and the energy of its individual corpuscles is approximately the required amount of one-half million electron-volts, corresponding to the complete annihilation of the positrons.

Positrons of high energy

The experimental results on the production of positrons out of radiation have been shown to be in approximate agreement with the theory for those processes where the quantum energies are not too high. Gamma radiations of quantum energy extending up to some 15 million electron-volts arise in certain nuclear transformations produced in the laboratory. Measurements of the absorption of these radiations and of the numbers and distribution in energy of the positive and negative electrons produced by these radiations are in sufficiently good agreement with the calculations of Oppenheimer, Heitler, and Bethe based on the Dirac theory to provide evidence for the essential correctness of the theory of absorption of gamma radiations in the range of quantum energy up to some 15 million electron-volts.

In the broad range of energies, however, which lies above 15 million electron-volts and extends up to at least 20,000 million electron-volts, such as the energies with which the cosmic-ray particles are endowed, the experiments have only very recently provided strong evidence leading to a detailed understanding of the absorption of photons and electrons in this range of energies and to an explanation of the cosmic-ray showers.

Closely related to the process of the production of positive and negative electrons out of radiation, is the one which may be considered its inverse, namely, the production of radiation through nuclear impacts by a positive or negative electron in its passage through matter. Direct measurements on the energy loss of electrons, in the energy range up to about 400 million electron-volts, in their traversals through thin plates of lead, have shown that the loss in energy due to direct ionization by the electrons is but a small fraction of the total energy loss, and that the loss in energy over that due to ionization is in good accord with that to be expected theoretically through the production of radiation by nuclear impact. Furthermore a small number of measurements at energies up to 1,000 million electron-volts has shown no significant deviation from the theoretical loss. These data on energy loss of high-energy electrons afford strong evidence that, at least in part, the origin of the cosmic-ray showers of photons and positive and negative electrons can be understood in terms of a chain of successive processes of photon production by radiative impacts with nuclei on the part of the high-energy positive and negative electrons, and the subsequent absorption of these photons in nuclear collisions resulting in the production of numerous positive-negative electron pairs which appear as the cosmic-ray showers. After more detailed theoretical computations have been carried out on the rate of building-up of positive and negative electron secondaries resulting from these multiple processes, and their subsequent removal through absorption, will a more adequate test of the theory be possible. At present, however, it is very difficult to doubt that the highly absorbable component of the primary cosmic-ray beam consists largely of electrons absorbed principally through the mechanisms discussed above, which give rise to the electron showers.

Until quite recently it was not clear that the high-energy positive and negative electrons which have now been shown to exhibit a high absorbability, behaved in a manner essentially differently from the cosmic-ray particles of highly penetrating character. These highly penetrating particles, although not free positive and negative electrons, appear to consist of both positive and negative particles of unit electric charge, and will provide interesting material for future study.

Figs. 5-11 show examples of cosmic-ray showers of positive and negative electrons, and Fig. 12* an example of a large energy loss of a fast positive electron. Figs. 5,6,7,8, and 11 were photographed at 4,300 meters above sea level, the remainder near sea level.

It is a pleasure to express my sincere gratitude to Professor Millikan and to Dr. Neddermeyer for the great part they have played in these investigations on the properties of positrons, and to the Carnegie Institution of Washington, whose funds administered to Professor Millikan have made the investigations possible.

* No reproduction of this figure was given in the original.

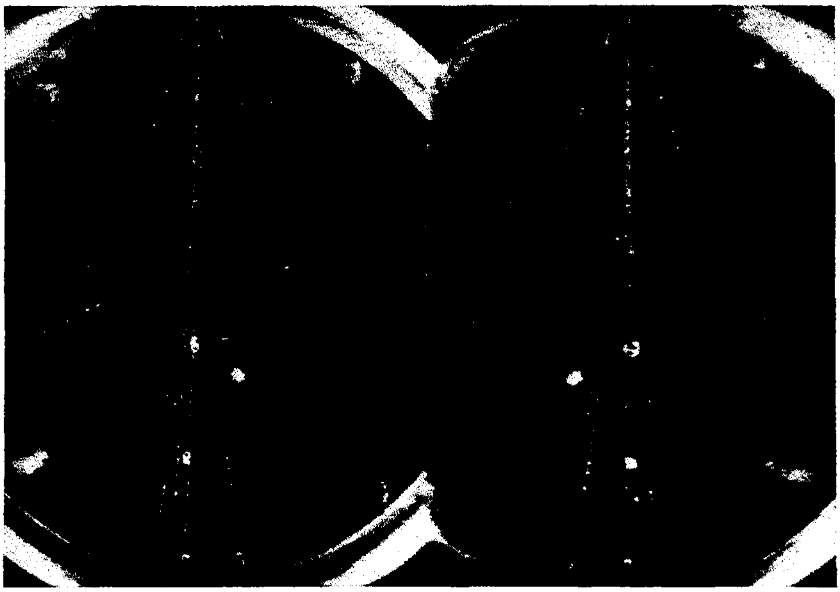

Fig. 5. A small cosmic-ray shower of positive and negative electrons. (Magnetic field 7,900 gauss.)

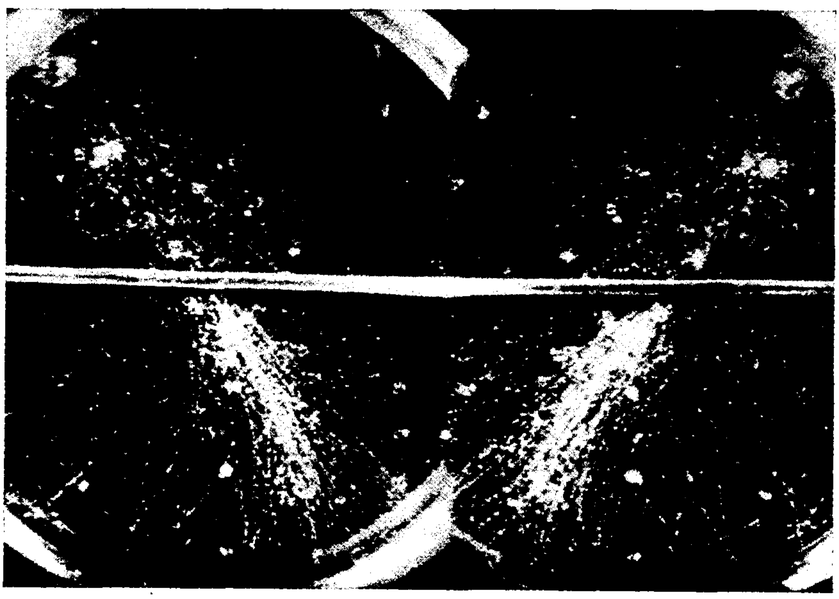

Fig. 6. A cosmic-ray shower of more than one hundred positive and negative electrons (Magnetic field 7,900 gauss.)

Fig. 7. A shower in which eight electrons (+ and -) strike the upper surface of a 0.35 cm lead plate, and more than fifteen emerge from its lower surface. This photograph is an example of the multiplication of shower tracks in a thin piece of absorbing material, due to the production by radiative impacts of photons and their absorption through pair-production (Magnetic field 7,900 gauss.)

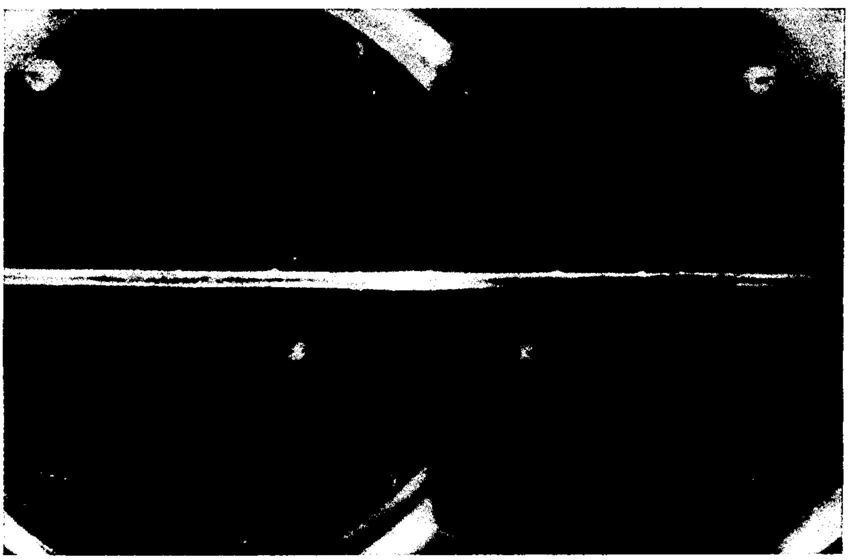

Fig. 8. A positive-negative electron pair (energies of negative and positive 4.6 and 140 million electron-volts respectively) generated in the gas (argon) of the chamber by a photon associated with the cosmic rays. (Magnetic field 7,900 gauss.)

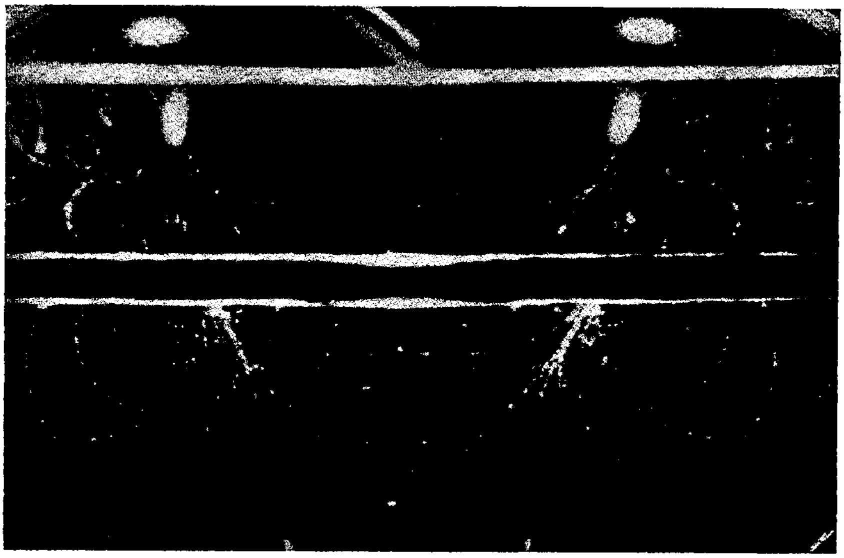

Fig. 9. A cosmic-ray shower of 22 positive and negative electrons produced by one or more photons initially incident on the upper surface of a 1 cm lead plate. (Magnetic field 17,000 gauss.)

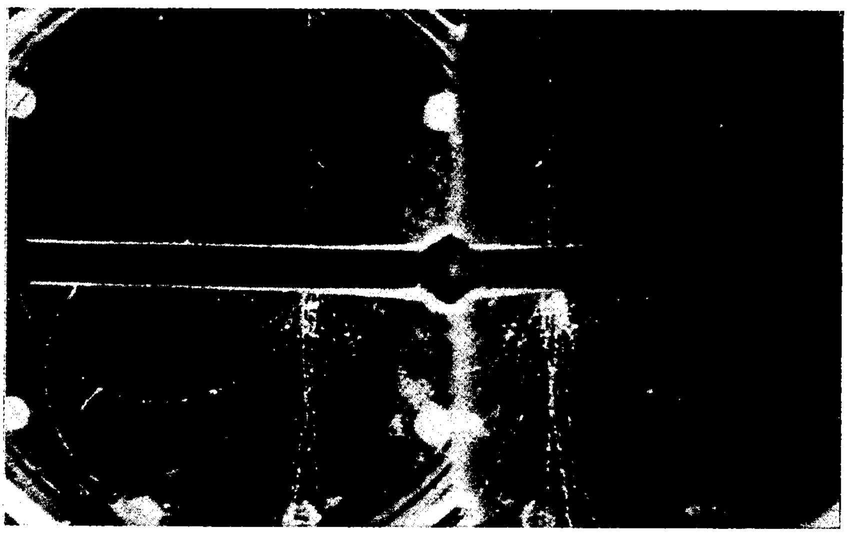

Fig. 10. Three high-energy cosmic-ray electrons incident on the upper surface of a 1 cm platinum plate. A shower of more than 20 positive and negative electrons emerges from the lower surface of the plate from a region below two of the three incident electrons. The shower appears as a result of the production of photons by radiative impacts and their absorption by pair-production in the platinum plate. (Magnetic field 7,900 gauss.)

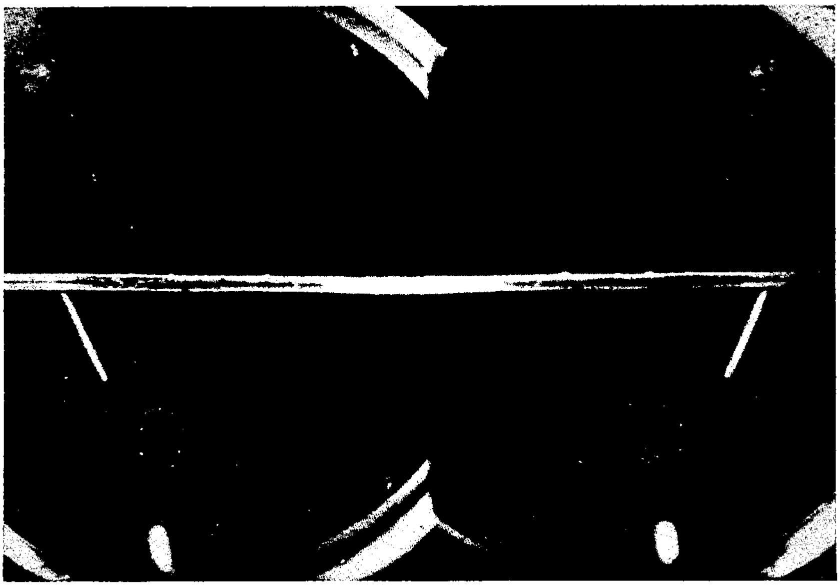

Fig. 11. A positron of 480 million electron-volts strikes a 0.35 cm lead plate. Below the plate three electrons appear having energies (in million electron-volts) respectively: positron 45, negatron 45, and positron 31. One of the tracks below the plate presumably represents the incident positron after passage through the plate, and the other two tracks a pair generated by the absorption of a photon generated in the plate. The energy lost in the plate by the incident positron is at least 435 million electron-volts and since the loss by ionization in a plate of this thickness should not be greater than 10 million electron-volts, the greater part of the energy lost by the positron in this instance must have appeared in the form of radiation. (Magnetic field 7,900 gauss.)

Biography

Carl David Anderson, who was born of Swedish parents -his father was Carl David Anderson and his mother Emma Adolfina Ajaxson- in New York City (USA) on 3rd September, 1905, has spent the bulk of his life in the United States. He graduated from the California Institute of Technology in 1927 with a B.Sc. degree in Physics and Engineering, and was awarded his Ph.D. degree by the same Institute, in 1930. For the period 1930-1933 he was Research Fellow there, subsequently (1933) Assistant Professor of Physics, and Professor of Physics (1939). During the war years (1941-1945) he was also active on projects for the National Defence Research Committee and the Office of Scientific Research and Development.

His early researches were in the field of X-rays. For his doctoral thesis he studied the space distribution of photoelectrons ejected from various gases by X-rays. In 1930, with Professor Millikan, he began his cosmic-ray studies which led in 1932 to the discovery of the positron. He has studied the energy distribution of cosmic-ray particles and the energy loss of very high speed electrons in traversing matter. In 1933 he and Dr. Neddermeyer obtained the first direct proof that gamma rays from ThC" generate positrons in their passage through material substances. Since 1933 he has continued his work on radiation and fundamental particles. Most of Anderson's researches and discoveries have been published in *The Physical Review* and *Science.*

Among the scientific honours bestowed upon him, in addition to the Nobel Prize, may be mentioned the following : Gold Medal of the American Institute of City of New York (1935); Sc.D. of Colgate University (1937); Elliott Cresson Medal of the Franklin Institute (1937); Presidential Certificate of Merit (1945); LL.D. Temple University (1949); John Ericsson Medal of the American Society of Swedish Engineers (1960).

In 1946 Anderson married Lorraine Bergman; they have two sons, Marshall and David.

Physics 1937

CLINTON JOSEPH DAVISSON

GEORGE PAGET THOMSON

<<for their experimental discovery of the diffraction of electrons by crystals>>

Physics 1937

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Nobel Prize for Physics for the year 1937 will today be delivered to Dr. C. J. Davisson and Professor G. P. Thomson for their discovery of the interference phenomena arising when crystals are exposed to electronic beams.

The study of the dispersion and diffraction phenomena produced by beams of electrons impinging on crystal surfaces was begun already in 1922 by Davisson and his collaborator Kunsman. These investigations soon obtained special actuality in connection with the theory of mechanical waves pronounced in 1923 by the Nobel Prize winner Prince de Broglie. According to this theory material particles are always linked with a system of travelling waves, a <<wave-packet>>, forming the constituent parts of matter and determining its movements. We might get a popular picture of the relation between a material particle and the associated mechanical waves, if we assume space filled with wave systems travelling with somewhat different velocities. In general these waves neutralize one another, but at certain points it happens that a great number of waves are in such a position as to reinforce one another and form a marked wave crest. This wave crest then corresponds to a material particle. Since, however, the waves travel with different velocity they will part from one another, and the wave crest disappears to be found again at a nearby point. The material particle has moved. The wave crest will thus travel, but the velocity with which this is done is quite different from the one with which the underlying wave systems move. The material particle in general moves at right angles to the surfaces of the mechanical waves, just as a ray of light is, as a rule, directed at right angles to the surface planes of the light waves.

The theory of de Broglie derived from analogies between the laws ruling the movement of a material particle and those applying in the case of the passage of a ray of light.

A great number of phenomena observed in optics can neither be explained nor described by the aid of rays of light, and this holds true especially of the diffraction and dispersion phenomena produced when light passes through a narrow slit or by a sharp edge. To explain those phenomena it is necessary to have recourse to the hypothesis of the propagation of light by means of waves.

In recent times, the existence of diffraction and interference phenomena has settled a dispute regarding the nature of a certain radiation. This time the X-rays were concerned. The question was whether these rays consist of particles ejected with great velocity or of electromagnetic waves.

The mechanical grids utilized for studying interference phenomena in optics let through the X-rays without diffraction. This might be due to the wavelength of these rays being so short that the grids became too wide. The Nobel Prize winner von Laue then got the ingenious idea to use as grids, crystals, the regularly arranged atoms of which could serve as diffraction centres. It was also stated that the X-rays in those grids gave rise to diffraction and interference phenomena; the X-rays consequently consisted of waves.

The mechanical waves of de Broglie now correspond to the waves of light and the path of the material particle to the passage of the ray of light.

In his theory de Broglie found a simple relation between the velocity of the material particle and the wavelength of the <<wave-packet>> associated with this particle. The greater the velocity of the particle the shorter is the wavelength. If the velocity of the particle is known, it is then possible to calculate, by means of the formula indicated by de Broglie, the wavelength and *vice versa*.

The theory of de Broglie of mechanical waves and the development of wave mechanics have been of radical importance to modern atom theory.

It is therefore quite natural that this revolutionary theory should become the object of assiduous research as to its consequences and of efforts to prove experimentally the existence of mechanical waves.

As has already been mentioned, Davisson had, together with his collaborator Kunsman, in the year before the theory of de Broglie was presented, started a series of experiments on the diffraction phenomena produced when a beam of electrons impinges with a certain velocity on the surface of a crystal. These experiments which were continued during the following years, gave, however, at the beginning results rather strange and hard to explain, probably due to the great experimental difficulties connected with the apparatus arrangement. In 1928, however, the investigations met with such a success that Davisson and his collaborator Germer were able to present the incontestable evidence, reached by experiments, of the existence of mechanical waves and of the correctness of the theory of de Broglie. Four months later Professor Thomson, who had been studying the same problem independently of Davisson and by the aid of a different apparatus equipment for his experiments, also confirmed de Broglie's theory.

For their experiments Davisson and Germer availed themselves of a cubic nickel crystal. Here the atoms are symmetrically arranged in planes parallel to the end surfaces of the crystal, the atoms forming a quadratic network in the planes. However, as radiation surface was not used the end plane of the cube but the triangular plane obtained, if an angle of the cube is symmetrically cut off. The atoms in this plane form a triangular network.

A minute bundle of electrons of determined velocity were emitted perpendicularly upon this plane. If we assume the incoming electrons replaced by mechanical waves, the planes of which are thus parallel to the surface of the crystal, these mechanical waves will strike the atoms lying in the surface simultaneously, and these atoms as centres will, in their turn, emit new mechanical waves in all directions. The waves going out in a certain direction can be studied and measured by the aid of a so-called Faraday chamber placed in this direction. In this chamber the mechanical waves cause the same effect as the corresponding electrons. In order to describe better how the outgoing radiation arises, let us suppose the receiving device placed so as to capture the waves going out parallel to the crystal plane and at right angles to one of the sides of the triangle. Parallel to this side the atoms lie in parallel rows with a certain distance between the rows, this distance having been determined beforehand by the aid of X-ray investigations. Every row now emits its wave. But the waves from the inner rows arrive later, due to the longer way they have to pass to reach the edge of the triangle. As a rule an irregular system of waves is thus obtained in which the waves neutralize each other, and consequently no outgoing wave is produced. If on the other hand the mechanical waves should be of such a wavelength that the distance between the rows of atoms becomes equal to the wavelength or to a multiple thereof, all the outgoing waves will be in phase and reinforce one another. In this case a wave system going out in the direction indicated is obtained or, if preferable, a bundle of outgoing electronic beams.

The experiments now showed at what velocities of the incoming electrons outgoing beams are produced, and these have, according to what has been stated above, a wavelength equal to the distance between the rows of atoms. Since thus the wavelength of the mechanical waves had been found and since the velocity of the corresponding electron was known, it was possible to check the formula of de Broglie. Davisson found that the theory agreed with the experiments except for 1 to 2%. Davisson and Germer examined the reflection of the electronic beams in various directions and obtained results which agreed with the wave theory.

During his experiments Davisson used electron beams with rather a low velocity corresponding to the one obtained when an electron is made to pass a voltage between 50 and 600 volts.

Thomson, on the other hand, for his experiments availed himself of swift electrons with a velocity corresponding to voltages between 10,000 and 80,000 volts. These swift electrons have afterwards proved to be of great use in connection with studies on the structure of matter.

For his experiments Thomson made use of exceedingly thin films of celluloid, gold, platinum, or aluminium. He made the electron beam fall perpendicularly upon the film and examined the diffraction figures produced on a fluorescent screen placed behind the film, or else had them reproduced on a photographic plate. The thickness of the films used for the experiments amounted to between 1/10,000 and 1/100,000 of a millimetre. Such a film now consists of innumerable small crystals of various directions. In accordance with what the theory indicates, there is generally obtained on the screen a series of concentric rings corresponding to the various directions of the planes in a crystal where a regularly arranged network of atoms can be found. From the diametre of a ring, the wavelength of the mechanical wave can be determined, and to make possible the production of a ring this wavelength must be in accordance with the spacing of the planes in the system of planes to which the ring corresponds. A similar method has been applied previously by Debye-Scherrer for X-rays analysis of the structure of crystals. Thomson found very good agreement with the theory of de Broglie. He further found that a magnetic field influencing the beams having passed the film produced a lateral movement of the image on the screen, which shows that these beams consist of bundles of electrons.

For the above-mentioned experiments electrons have been employed as matter; later investigations have confirmed the correctness of de Broglie's theory also for such cases where beams of molecules, atoms, and atom nuclei have been used.

The purpose of the said experiments was to verify the theory of de Broglie, and to this end was utilized the knowledge of the arrangement of the atoms in a crystal, this knowledge having been previously acquired as a result of investigations by means of X-rays. Now that the law of de Broglie has become known and acknowledged, the opposite way has been taken. From the law of de Broglie we know the wavelength of the mechanical waves accompanying an electronic beam with a certain velocity of the electrons. By changing this velocity we can then obtain electronic waves with known wavelengths. By application of one or the other of the investigation methods mentioned above we can find the distances between the various atom planes within the crystal and thus also the structure of the crystal. The procedure is here the same as the one previously applied to determine the structure of crystals by means of X-rays. We have thus obtained a new method for such investigation, but the two methods have found very different fields of application due to the different nature of the beams employed. The X-rays are pure electromagnetic rays like the rays of light, and they therefore influence but slightly the atoms of the crystal, and owing to this circumstance easily traverse the crystal structure. From the same reason the diffracted rays are comparatively feeble, and many hours' exposure is therefore required to record X-ray diagrams. The mechanical waves, on the other hand, are associated with electrical charges which are very strongly influenced by the charges of the crystal atoms. The mechanical waves will therefore be rapidly absorbed in the crystal, and the interference figures obtained only come from an exceedingly thin surface layer. In return the intensity of the diffracted or reflected bundles of electrons becomes very great, and the time of exposure required is consequently extremely short, in many cases only a fraction of a second. These properties of the electronic beams make them an exceedingly important complement to the X-rays as far as researches on the structure of matter are concerned. At the important investigations of the structure of surfaces good results can be attained only by the new method, since the images of the X-rays are influenced by the matter lying behind the surface layer. By the aid of electronic beams it has thus been possible to explain how the structure of the surfaces of metals is changed by various mechanical, thermal, or chemical treatment. It has also been possible to ascertain the properties of thin layers of gases and powder. On account of the rapid exposure which the electronic beams permit, we can follow the course of the changes occurring in connection with the oxidization of metals and also observe the corrosion phenomenon in iron and steel for various thermal treatment as well as the chemical process ensuing when metals are attacked by corrosive substances. The intensity of radiation is so great that one can easily carry out investigations of the structure of crystals with a mass of less than a millionth of a gram. This has made it possible to discover in certain substances exceedingly minute crystalline structures, which it would not have been possible to find by means of X-ray investigations.

It would bring us too far here to enter upon the multitude of experimental results furnished by the method with electronic beams, especially as new fields of application of the electron beam are incessantly being opened up within the spheres of physical and chemical research.

Dr. Davisson. When you found that electron beams touching crystals give rise to phenomena of diffraction and interference, this signified in itself a discovery that widened essentially our knowledge of the nature of electrons. But this discovery has proved to be of still greater importance. Your researches concerning these phenomena resulted in your presenting the first positive, experimental evidence of the wave nature of matter. The investigation methods that you and Professor Thomson have elaborated and the further research work carried out by both of you have provided science with a new, exceedingly important instrument for examining the structure of matter, an instrument constituting a very valuable complement to the earlier method which makes use of the X-ray radiation. The new investigations have already furnished manifold new, significant results within the fields of physics and chemistry and of the practical application of these sciences.

On behalf of the Royal Swedish Academy of Sciences I congratulate you on your important discoveries, and I now ask you to receive your Nobel Prize from the hands of His Majesty.

The Royal Swedish Academy of Sciences much regrets that Professor Thomson has not had the opportunity of being present on this occasion to receive in person his Nobel Prize. The prize will now instead be delivered to His Excellency the Minister of Great Britain.

Your Excellency. Permit me to request you to receive on behalf of Professor Thomson the Nobel Prize for Physics from the hands of His Majesty.

CLINTON J. DAVISSON

The discovery of electron waves

Nobel Lecture, December 13, 1937

That streams of electrons possess the properties of beams of waves was discovered early in 1927 in a large industrial laboratory in the midst of a great city, and in a small university laboratory overlooking a cold and desolate sea. The coincidence seems the more striking when one remembers that facilities for making this discovery had been in constant use in laboratories throughout the world for more than a quarter of a century. And yet the coincidence was not, in fact, in any way remarkable. Discoveries in physics are made when the time for making them is ripe, and not before; the stage is set, the time is ripe, and the event occurs - more often than not at widely separated places at almost the same moment.

The setting of the stage for the discovery of electron diffraction was begun, one may say, by Galileo. But I do not propose to emulate the gentleman who began a history of his native village with the happenings in the Garden of Eden. I will take, as a convenient starting-point, the events which led to the final acceptance by physicists of the idea that light for certain purposes must be regarded as corpuscular. This idea after receiving its quietus at the hands of Thomas Young in 1800 returned to plague a complacent world of physics in the year 1899. In this year Max Planck put forward his conception that the energy of light is in some way quantized. A conception which, if accepted, supplied, as he showed, a means of explaining completely the distribution of energy in the spectrum of black-body radiation. The quantization was such that transfers of energy between radiation and matter occurred abruptly in amounts proportional to the radiation frequency. The factor of proportionality between these quantities is the ever-recurring Planck constant, h. Thus was reborn the idea that light is in some sense corpuscular.

How readily this circumstantial evidence for a corpuscular aspect of light would have been accepted as conclusive must remain a matter of conjecture, for already the first bits of direct evidence pointing to the same conclusion were being taken down from the scales and meters of the laboratory; the truth about light was being wrung from Nature - at times, and in this case, a most reluctant witness.

In an extended examination carried on chiefly by Richardson and K. T. Compton, Hughes, and Millikan, it was brought out that light imparts energy to individual electrons in amounts proportional to its frequency and finally that the factor of proportionality between energy and frequency is just that previously deduced by Planck from the black-body spectrum. The idea of pressing the witness on the latter point had come from Einstein who outplancked Planck in not only accepting quantization, but in conceiving of light quanta as actual small packets or particles of energy transferable to single electrons *in toto*.

The case for a corpuscular aspect of light, now exceedingly strong, became overwhelmingly so when in 1922 A. H. Compton showed that in certain circumstances light quanta - photons as they were now called - have elastic collisions with electrons in accordance with the simple laws of particle dynamics. What appeared, and what still appears to many of us as a contradiction in terms had been proved true beyond the least possible doubt - light was at once a flight of particles and a propagation of waves; for light persisted, unreasonably, to exhibit the phenomenon of interference.

Troubles, it is said, never come singly, and the trials of the physicist in the early years of this century give grounds for credence in the pessimistic saying. Not only had light, the perfect child of physics, been changed into a gnome with two heads - there was trouble also with electrons. In the open they behaved with admirable decorum, observing without protest all the rules of etiquette set down in Lorentz' manual, but in the privacy of the atom they indulged in strange and unnatural practices; they oscillated in ways which no well-behaved mechanical system would deem proper. What was to be said of particles which were ignorant apparently of even the rudiments of dynamics? Who could apologize for such perversity - rationalize the data of spectroscopy? A genius was called for, and a genius appeared. In 1913 Niels Bohr gave us his strange conception of <<stationary>. orbits in which electrons rotated endlessly without radiating, of electrons disappearing from one orbit and reappearing, after brief but unexplained absences, in another. It was a weird picture-a picture to delight a surrealist-but one which fascinated the beholder, for in it were portrayed with remarkable fidelity the most salient of the orderly features which spectroscopic data were then known to possess; there was the Balmer series! and there the Rydberg constant! - correct to the last significant digit! It was a masterpiece. It is important to note that in achieving this *tour deforce* Bohr made judicious use of the constant which Planck had extracted from the black-body spectrum, the constant *h*.

It looked at this time - in the year 1913 - as if the authentic key to the spectra had at last been found, as if only time and patience would be needed to resolve their riddles completely. But this hope was never fulfilled. The first brilliant triumphs of the theory were followed by yet others, but soon the going became distressingly difficult, and finally, despite the untiring efforts of countless helpers, the attack came virtually to a standstill. The feeling grew that deeply as Bohr had dived he had not, so to speak, touched bottom. What was wanted, it was felt, was a new approach, a new theory of the atom which would embrace necessarily all the virtues of the Bohr theory and go beyond it - a theory which would contain some vaguely sensed unifying principle which, it was felt, the Bohr theory lacked.

Such an underlying principle had been sought for almost from the first. By 1924 one or two ideas of promise had been put forward and were being assiduously developed. Then appeared the brilliant idea which was destined to grow into that marvelous synthesis, the present-day quantum mechanics. Louis de Broglie put forward in his doctor's thesis the idea that even as light, so matter has a duality of aspects; that matter like light possesses both the properties of waves and the properties of particles. The various <<restrictions, of the Bohr theory were viewed as conditions for the formation of standing electron wave patterns within the atom.

Reasoning by analogy from the situation in optics and aided by the clue that Planck's constant is a necessary ingredient of the Bohr's theory, de Broglie assumed that this constant would connect also the particle and wave aspects of electrons, if the latter really existed. De Broglie assumed that, as with light, the correlation of the particle and wave properties of matter would be expressed by the relations:

(Energy of particle) $E = h\nu$ (*frequency,* i.e. waves/unit time)
(Momentum of particle) $p = h\sigma$ (wave number, i.e. waves/unit distance)

The latter may be written in the more familiar form $\lambda = h/p$, where λ represents wavelength.

Perhaps no idea in physics has received so rapid or so intensive development as this one. De Broglie himself was in the van of this development but the chief contributions were made by the older and more experienced Schrödinger.

In these early days - eleven or twelve years ago - attention was focussed on electron waves in atoms. The wave mechanics had sprung from the atom, so to speak, and it was natural that the first applications should be to the atom. No thought was given at this time, it appears, to electrons in free flight. It was implicit in the theory that beams of electrons like beams of light would exhibit the properties of waves, that scattered by an appropriate grating they would exhibit diffraction, yet none of the chief theorists mentioned this interesting corollary. The first to draw attention to it was Elsasser, who pointed out in 1925 that a demonstration of diffraction would establish the physical existence of electron waves. The setting of the stage for the discovery of electron diffraction was now complete.

It would be pleasant to tell you that no sooner had Elsasser's suggestion appeared than the experiments were begun in New York which resulted in a demonstration of electron diffraction - pleasanter still to say that the work was begun the day after copies of de Broglie's thesis reached America. The true story contains less of perspicacity and more of chance. The work actually began in 1919 with the accidental discovery that the energy spectrum of secondary electron emission has, as its upper limit, the energy of the primary electrons, even for primaries accelerated through hundreds of volts; that there is, in fact, an elastic scattering of electrons by metals.

Out of this grew an investigation of the distribution-in-angle of these elastically scattered electrons. And then chance again intervened; it was discovered, purely by accident, that the intensity of elastic scattering varies with the orientations of the scattering crystals. Out of this grew, quite naturally, an investigation of elastic scattering by a single crystal of predetermined orientation. The initiation of this phase of the work occurred in 1925, the year following the publication of de Broglie's thesis, the year preceding the first great developments in the wave mechanics. Thus the New York experiment was not, at its inception, a test of the wave theory. Only in the summer of 1926, after I had discussed the investigation in England with Richardson, Born, Franck and others, did it take on this character.

The search for diffraction beams was begun in the autumn of 1926, but not until early in the following year were any found - first one and then twenty others in rapid succession. Nineteen of these could be used to check the relationship between wavelength and momentum and in every case the correctness of the de Broglie formula, $\lambda = h/p$ was verified to within the limit of accuracy of the measurements.

I will recall briefly the scheme of the experiment. A beam of electrons of predetermined speed was directed against a (III) face of a crystal of nickel as indicated schematically in Fig. 1. A collector designed to accept only elastically scattered electrons and their near neighbors, could be moved on an arc about the crystal. The crystal itself could be revolved about the axis of the incident beam. It was possible thus to measure the intensity of elastic scattering in any direction in front of the crystal face with the exception of those directions lying within 10 or 15 degrees of the primary beam.

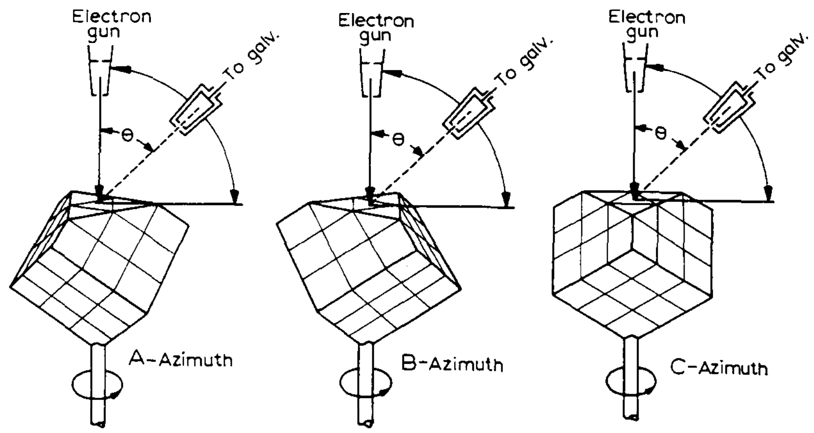

Fig. I. Schematic diagram showing disposition of primary beam, nickel crystal, and collector. Crystal shown revolved to bring one principal azimuth after another into plane of observation.

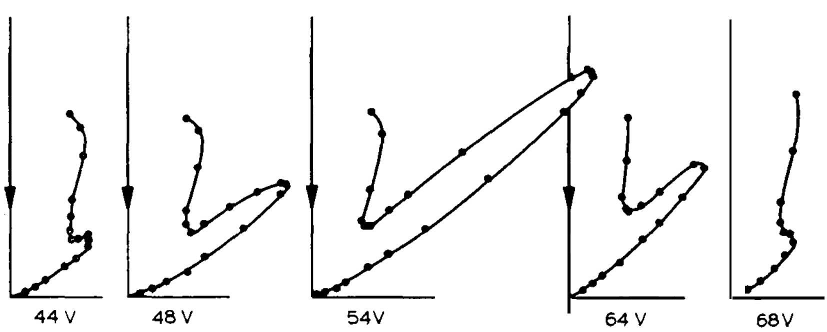

Fig. 2. Polar diagram showing intensity of elastic scattering in A-azimuth (Fig. I) as function of latitude angle, for series of primary-beam voltages.

The curves reproduced in Fig. 2 show the distribution-in-angle of intensity for a particular azimuth of the crystal. The curves are for a series of electron speeds, therefore, for a series of electron wavelengths. For a particular wavelength a diffraction beam shines out. Setting the collector on this beam at its brightest, and revolving the crystal, the intensity was found to vary in azimuth as illustrated in Fig. 3. The high peak on the left represents the cross-section-in-azimuth of the beam shown in Fig. 2. Two similar peaks mark the positions of companion beams which with the first form a set of three, as required by the threefold symmetry of the crystal about its (III) directions - the direction of the incident beam. The lesser intermediate peaks are due to a different set of beams which is not here fully developed.

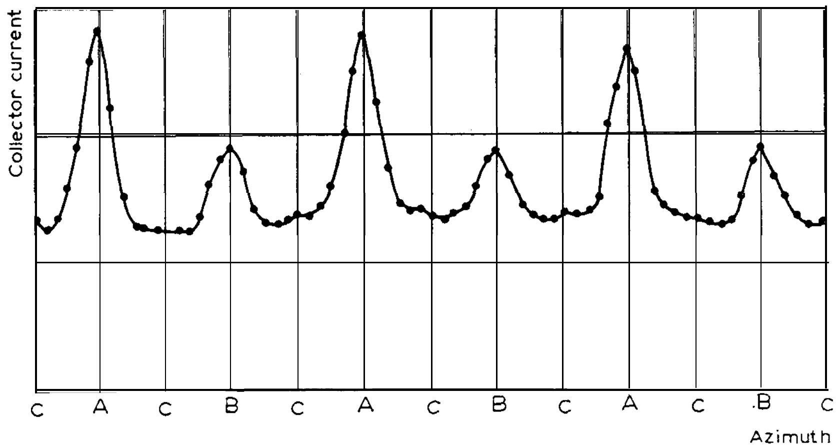

Fig. 3. Curve showing intensity of elastic scattering of 54-volt primary beam as function of azimuth for latitude of peak in 54-volt curve of Fig. 2.

The de Broglie relation was tested by computing wavelengths from the angles of the diffraction beams and the known constant of the crystal, and comparing these with corresponding wavelengths computed from the formula $\lambda = h/p$, where p, the momentum of the electrons, was obtained from the potential used to accelerate the beam and the known value of e/m for electrons. If wavelengths computed from the formula agreed with those obtained from the diffraction data, the de Broglie relation would be verified. How nearly the theoretical values agreed with the experimental is illustrated in Fig. 4. For perfect agreement all points would fall on the line drawn through the origin.

You will realize without my telling you that this series of experiments extending in time over a period of eight or nine years and requiring the construction and manipulation of intricate apparatus was not made by me alone. From first to last a considerable number of my colleagues contributed to the investigation. Chief among these were my two exceptionally able collaborators, Dr. C. H. Kunsman and Dr. L. H. Germer. Dr. Kunsman worked with me throughout the early stages of the investigation, and Dr. Germer,

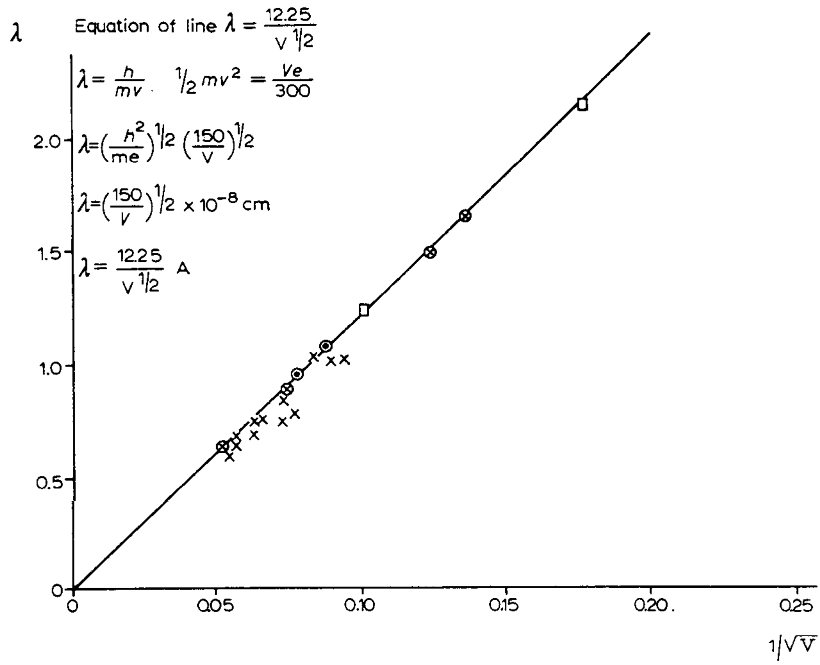

Fig. 4. Test of the de Broglie formula $\lambda = k/p = h/mv$. Wavelength computed from diffraction data plotted against $1/V^{½}$, (V, primary-beam voltage). For precise verification of the formula all points should fall on the line λ, $= 12.25/V^{½}$ plotted in the diagram. (x From observations with diffraction apparatus; o same, particularly reliable; same, grazing beams. ⊙ From observations with reflection apparatus.)

to whose skill and perseverance a great part of the success of the definitive experiments is due, succeeded Dr. Kunsman in 1924.

I would like also at this time to express my admiration of the late Dr. H. D. Arnold, then Director of Research in the Bell Telephone Laboratories, and of Dr. W. Wilson, my immediate superior, who were sufficiently far-sighted to see in these researches a contribution to the science of communication. Their vision was in fact accurate, for today in our, as in other industrial laboratories, electron diffraction is applied with great power and efficacy for discerning the structures of materials.

But neither of this nor of the many beautiful and important researches which have been made in electron diffraction in laboratories in all parts of the world since 1927 will I speak today. I will take time only to express my admiration of the beautiful experiments - differing from ours in every respect - by which Thomson in far-away Aberdeen also demonstrated electron diffraction and verified de Broglie's formula at the same time as we in New York. And to mention, as closely related to the subject of this discourse, the difficult and beautifully executed experiments by which Stern and Estermann in 1929 showed that atomichy drogen also is diffracted in accordance with the de Broglie-Schrödinger theory.

Important and timely as was the discovery of electron diffraction in inspiring confidence in the physical reality of material waves, our confidence in this regard would hardly be less today, one imagines, were diffraction yet to be discovered, so great has been the success of the mechanics built upon the conception of such waves in clarifying the phenomena of atomic and subatomic physics.

Biography

Clinton Joseph Davisson was born at Bloomington, Illinois, U.S.A., October 22, 1881, son of Joseph Davisson, an artisan, native of Ohio, descendant of early Dutch and French settlers of Virginia, Union veteran of the American Civil War, and Mary Calvert, a school-teacher, native of Pennsylvania, of English and Scotch parentage.

He attended the Bloomington public schools, and on graduation from High School in 1902 was granted a scholarschip by the University of Chicago for proficiency in mathematics and physics. In September of that year he entered the University of Chicago and came at once under the influence of Professor R. A. Millikan. Unable for financial reasons to continue at Chicago the following year he found employment with a telephone company in his home town. In January 1904 he was appointed assistant in physics at Purdue University on recommendation of Professor Millikan. He returned to Chicago in June 1904 and remained in residence at the University until August 1905. In September 1905, again on the recommendation of Professor Millikan, he was appointed part-time instructor in physics at Princeton University. This post he held until 1910, studying, as his duties permitted, under Professor Francis Magie, Professor E. P. Adams, Professor (later Sir) James Jeans and particularly under Professor 0. W. Richardson. During a part of this period Davisson returned to the University of Chicago for the summer sessions and in August 1908 received a B.S. degree from that institution.

He was awarded a Fellowship in Physics at Princeton for the year 1910-1911 and during that year completed requirements for the degree of Ph.D. which he received June 1911. His thesis, under Professor Richardson, was *On The Thermal Emission of Positive Ions From Alkaline Earth Salts.*

From September 1911 until June 1917 he was an instructor in the Department of Physics at the Carnegie Institute of Technology, Pittsburgh, Pa. During the summer of 1913 he worked in the Cavendish Laboratory under Professor (later Sir) J. J. Thomson.

In April 1917 he was refused enlistment in the United States Army. In

June of the same year he accepted war-time employment in the Engineering Department of the Western Electric Company (later Bell Telephone Laboratories), New York City-at first for summer, then, on leave of absence from Carnegie Tech., for the duration of the World War. At the end of the war he resigned an assistant professorship to which he had been appointed at Carnegie Tech. to continue as a Member of the Technical Staff of the Telephone Laboratories.

The series of investigations which led to the discovery of electron diffraction in 1927 was begun in 1919 and was continued into 1929 with the collaboration first of Dr. C. H. Kunsman, and from 1924 on, of Dr. L. H. Germer. During the same period researches were carried on in thermal radiation with the collaboration of Mr. J. R. Weeks, and in thermionics with Dr. H. A. Pidgeon and Dr. Germer.

From 1930-1937 Dr. Davisson devoted himself to the study of the theory of electron optics and to applications of this theory to engineering problems. He then investigated the scattering and reflection of very slow electrons by metals. During World War II he worked on the theory of electronic devices and on a variety of crystal physics problems.

In 1946 he retired from Bell Telephone Laboratories after 29 years of service. From 1947 to 1949, he was Visiting Professor of Physics at the University of Virginia, Charlottesville, Va.

In 1928 he was awarded the Comstock Prize by the National Academy of Sciences, in 1931 the Elliott Cresson Medal by the Franklin Institute, and in 1935 the Hughes Medal by the Royal Society (London), and in 1941 the Alumni Medal by the University of Chicago. He held honorary doctorates from Purdue University, Princeton University, the University of Lyon and Colby College.

In 1911 he married Charlotte Sara Richardson, a sister of Professor Richardson. He died in Charlottesville on February 1, 1958, at the age of 76, and was survived by his wife, three sons and one daughter.

GEORGE P. THOMSON

Electronic waves

Nobel Lecture, June 7, 1938

Ever since last November, I have been wanting to express in person my gratitude to the generosity of Alfred Nobel, to whom I owe it that I am privileged to be here today, especially since illness prevented me from doing so at the proper time. The idealism which permeated his character led him to make his magnificent foundation for the benefit of a class of men with whose aims and viewpoint his own scientific instincts and ability had made him naturally sympathetic, but he was certainly at least as much concerned with helping science as a whole, as individual scientists. That his foundation has been as successful in the first as in the second, is due to the manner in which his wishes have been carried out. The Swedish people, under the leadership of the Royal Family, and through the medium of the Royal Academy of Sciences, have made the Nobel Prizes one of the chief causes of the growth of the prestige of science in the eyes of the world, which is a feature of our time. As a recipient of Nobel's generosity I owe sincerest thanks to them as well as to him.

The goddess of learning is fabled to have sprung full-grown from the brain of Zeus, but it is seldom that a scientific conception is born in its final form, or owns a single parent. More often it is the product of a series of minds, each in turn modifying the ideas of those that came before, and providing material for those that come after. The electron is no exception.

Although Faraday does not seem to have realized it, his work on electrolysis, by showing the unitary character of the charges on atoms in solution, was the first step. Clerk Maxwell in 1873 used the phrase a <<molecule of electricity>> and von Helmholtz in 1881 speaking of Faraday's work said <<If we accept the hypothesis that elementary substances are composed of atoms, we cannot well avoid concluding that electricity also is divided into elementary portions which behave like atoms of electricity.>> The hypothetical atom received a name in the same year when Johnstone Stoney of Dublin christened it <<electron>>, but so far the only property implied was an electron charge.

The last year of the nineteenth century saw the electron take a leading place amongst the conceptions of physics. It acquired not only mass but universality, it was not only electricity but an essential part of all matter. If among the many names associated with this advance I mention that of J. J. Thomson I hope you will forgive a natural pride. It is to the great work of Bohr that WC owe the demonstration of the connection between electrons and Planck's quantum which gave the electron a dynamics of its own. A few years later, Goudsmit and Uhlenbeck, following on an earlier suggestion by A. H. Compton showed that it was necessary to suppose that the electron had spin. Yet even with the properties of charge, mass, spin and a special mechanics to help it, the electron was unable to carry the burden of explaining the large and detailed mass of experimental data which had accumulated. L. de Broglie, working originally on a theory of radiation, produced as a kind of by-product the conception that any particle and in particular an electron, was associated with a system of waves. It is with these waves, formulated more precisely by Schrödinger, and modified by Dirac to cover the idea of spin, that the rest of my lecture will deal.

The first published experiments to confirm de Broglie's theory were those of Davisson and Germer, but perhaps you will allow me to describe instead those to which my pupils and I were led by de Broglie's epoch-making conception.

A narrow beam of cathode rays was transmitted through a thin film of matter. In the earliest experiment of the late Mr. Reid this film was of celluloid, in my own experiment of metal. In both, the thickness was of the order of 10^{-6} cm. The scattered beam was received on a photographic plate normal to the beam, and when developed showed a pattern of rings, recalling optical halos and the Debye-Scherrer rings well known in the corresponding experiment with X-rays. An interference phenomenon is at once suggested. This would occur if each atom of the film scattered in phase a wavelet from an advancing wave associated with the electrons forming the cathode rays. Since the atoms in each small crystal of the metal are regularly spaced, the phases of the wavelets scattered in any fixed direction will have a definite relationship to one another. In some directions they will agree in phase and build up a strong scattered wave, in others they will destroy one another by interference. The strong waves are analogous to the beams of light diffracted by an optical grating. At the time, the arrangement of the atoms in celldoid was not known with certainty and only general conclusions could be drawn, but for the metals it had been determined previously by the use of X-rays. According to de Broglie's theory the wavelength associated with an electron is *h/mv* which for the electrons used (cathode rays of 20 to 60,000 volts energy) comes out from 8×10^{-9} to 5×10^{-9} cm. I do not wish to trouble you with detailed figures and it will be enough to say that the patterns on the photographic plates agreed quantitatively, in all cases, with the distribution of strong scattered waves calculated by the method I have indicated. The agreement is good to the accuracy of the experiments which was about 1%. There is no adjustable constant, and the patterns reproduce not merely the general features of the X-ray patterns but details due to special arrangements of the crystals in the films which were known to occur from previous investigation by X-rays. Later work has amply confirmed this conclusion, and many thousands of photographs have been taken in my own and other laboratories without any disagreement with the theory being found. The accuracy has increased with the improvement of the apparatus, perhaps the most accurate work being that of v. Friesen of Uppsala who has used the method in a precision determination of *e* in which he reaches an accuracy of 1 in 1,000.

Before discussing the theoretical implications of these results there are two modifications of the experiments which should be mentioned. In the one, the electrons after passing through the film are subject to a uniform magnetic field which deflects them. It is found that the electrons whose impact on the plate forms the ring pattern are deflected equally with those which have passed through holes in the film. Thus the pattern is due to electrons which have preserved unchanged the property of being deflected by a magnet. This distinguishes the effect from anything produced by X-rays and shows that it is a true property of electrons. The other point is a practical one, to avoid the need for preparing the very thin films which are needed to transmit the electrons, an apparatus has been devised to work by reflection, the electrons striking the diffracting surface at a small glancing angle. It appears that in many cases the patterns so obtained are really due to electrons transmitted through small projections on the surface. In other cases, for example when the cleavage surface of a crystal is used, true reflection occurs from the Bragg planes.

The theory of de Broglie in the form given to it by Schrödinger is now known as wave mechanics and is the basis of atomic physics. It has been applied to a great variety of phenomena with success, but owing largely to mathematical difficulties there are not many cases in which an accurate comparison is possible between theory and experiment. The diffraction of fast electrons by crystals is by far the severest numerical test which has been made and it is therefore important to see just what conclusions the excellent agreement between theory and these experiments permits us to draw.

The calculations so far are identical with those in the corresponding case of the diffraction of X-rays. The only assumption made in determining the directions of the diffracted beams is that we have to deal with a train of wave of considerable depth and with a plane wave-front extending over a considerable number of atoms. The minimum extension of the wave system sideways and frontways can be found from the sharpness of the lines. Taking v. Friesen's figures, it is at least 225 waves from back to front over a front of more than 200 Å each way.

But the real trouble comes when we consider the physical meaning of the waves. In fact, as we have seen, the electrons blacken the photographic plate at those places where the waves would be strong. Following Bohr, Born, and Schrödinger, we can express this by saying that the intensity of the waves at any place measures the *probability* of an electron manifesting itself there. This view is strengthened by measurements of the relative intensities of the rings, which agree well with calculations by Mott based on Schrödinger's equation. Such a view, however successful as a formal statement is at variance with all ordinary ideas. Why should a particle appear only in certain places associated with a set of waves? Why should waves produce effects only through the medium of particles? For it must be emphasized that in these experiments each electron only sensitizes the photographic plate in one minute region, but in that region it has the same powers of penetration and photographic action as if it had never been diffracted. We cannot suppose that the energy is distributed throughout the waves as in a sound or water wave, the wave is only effective in the one place where the electron appears. The rest of it is a kind of phantom. Once the particle has appeared the wave disappears like a dream when the sleeper wakes. Yet the motion of the electron, unlike that of a Newtonian particle, is influenced by what happens over the whole front of the wave, as is shown by the effect of the size of the crystals on the sharpness of the patterns. The difference in point of view is fundamental, and we have to face a break with ordinary mechanical ideas. Particles have not a unique track, the energy in these waves is not continuously distributed, probability not determinism governs nature.

But while emphasizing this fundamental change in outlook, which I believe to represent an advance in physical conceptions, I should like to point out several ways in which the new phenomena fit the old framework better than is often realized. Take the case of the influence of the size of the crystals on the sharpness of the diffracted beams, which we have just mentioned. On the wave theory it is simply an example of the fact that a diffraction grating with only a few lines has a poor resolving power. Double the number of the lines and the sharpness of the diffracted beams is doubled also. However if there are already many lines, the *angular* change is small. But imagine a particle acted on by the material which forms the slits of the grating, and suppose the forces such as to deflect it into one of the diffracted beams. The forces due to the material round the slits near the one through which it passes will be the most important, an increase in the number of slits will affect the motion but the angular deflection due to adding successive slits will diminish as the numbers increase. The law is of a similar character, though no simple law of force would reproduce the wave effect quantitatively.

Similarly for the length of the wave train. If this were limited by a shutter moving so quickly as to let only a short wave train pass through, the wave theory would require that the velocity of the particle would be uncertain over a range increasing with the shortness of the wave train, and corresponding to the range of wavelengths shown by a Fourier analysis of the train. But the motion of the shutter might well be expected to alter the velocity of a particle passing through, just before it closed.

Again, on the new view it is purely a matter of chance in which of the diffracted beams of different orders an electron appears. If the phenomenon were expressed as the classical motion of a particle, this would have to depend on the initial motion of the particle, and there is no possibility of determining this initial motion without disturbing it hopelessly. There seems no reason why those who prefer it should not regard the diffraction of electrons as the motion of particles governed by laws which simulate the character of waves, but besides the rather artificial character of the law of motion, one has to ascribe importance to the detailed initial conditions of the motion which, as far as our present knowledge goes, are necessarily incapable of being determined. I am predisposed by nature in favour of the most mechanical explanations possible, but I feel that this view is rather clumsy and that it might be best, as it is certainly safer, to keep strictly to the facts and regard the wave equation as merely a way of predicting the result of experiments. Nevertheless, the view I have sketched is often a help in thinking of these problems. We are curiously near the position which Newton took over his theory of optics, long despised but now seen to be far nearer the truth than that of his rivals and successors.

<< 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 undulating Motion, and all Bodies by percussion excite vibrations in the Air : so the Rays of Light, by impinging on any refracting or reflecting Surface, excite vibrations 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 when any Ray is in that part of the vibration which conspires with its Motion, it easily breaks through a refracting Surface, but when it is in the contrary part of the vibration which impedes its Motion, it is easily reflected; and, by consequence, 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.>>

Although the experiments in diffraction confirm so beautifully the de Broglie-Schrödinger wave theory, the position is less satisfactory as regards the extended theory due to Dirac. On this theory the electron possesses magnetic properties and the wave requires four quantities instead of one for its specification. This satisfies those needs of spectroscopy which led to the invention of the spinning electron. It suggests however that electronic waves could be polarized and that the polarized waves might interact with matter in an anisotropic manner. In fact detailed calculations by Mott indicate that if Dirac electrons of 140 kV energy are scattered twice through 90° by the nuclei of gold atoms the intensity of the scattered beam will differ by 16% according to whether the two scatterings are in the same or in opposite directions. Experiments by Dymond and by myself have established independently that no effect of this order of magnitude exists, when the scattering is done by gold foils. While there is a slight possibility that the circumnuclear electrons, or the organization of the atoms into crystals might effect the result, it seems very unlikely. Some of the theorists have arrived at results conflicting with Mott, but I understand that their work has been found to contain errors. At present there seems no explanation of this discrepancy which throws doubt on the validity of the Dirac equations in spite of their success in predicting the positive electron.

I should be sorry to leave you with the impression that electron diffraction was of interest only to those concerned with the fundamentals of physics. It has important practical applications to the study of surface effects. You know how X-ray diffraction has made it possible to determine the arrangement of the atoms in a great variety of solids and even liquids. X-rays are very penetrating, and any structure peculiar to the surface of a body will be likely to be overlooked, for its effect is swamped in that of the much greater mass of underlying material. Electrons only affect layers of a few atoms, or at most tens of atoms, in thickness, and so are eminently suited for the purpose. The position of the beams diffracted from a surface enables us, at least in many cases, to determine the arrangement of the atoms in the surface. Among the many cases which have already been studied I have only time to refer to one, the state of the surface of polished metals. Many years ago Sir George Beilby suggested that this resembled a supercooled liquid which had flowed under the stress of polishing. A series of experiments by electron diffraction carried out at the Imperial College in London has confirmed this conclusion. The most recent work due to Dr. Cochrane has shown that though this amorphous layer is stable at ordinary temperature as long as it remains fixed to the mass of the metal, it is unstable when removed, and recrystalizes after a few hours. Work by Professor Finch on these lines has led to valuable conclusions as to the wear on the surfaces of cylinders and pistons in petrol engines.

It is in keeping with the universal character of physical science that this single small branch of it should touch on the one hand on the fundamentals of scientific philosophy and on the other, questions of everyday life.

Biography

George Paget Thomson was born in 1892 at Cambridge, the son of the late Sir J. J. Thomson (then Professor of Physics at Cambridge University), a Nobel Prize winner who, more than anyone else, was responsible for the discovery of the electron, and Rose Elisabeth Paget, daughter of the late Sir George Paget, Regius Professor of Medicine at Cambridge.

George Thomson went to school in Cambridge, and then up to the University. As an undergraduate at Trinity College he took mathematics followed by physics, and had done a year's research under his father when the 1914-1918 war broke out.

He joined the Queen's Regiment of Infantry as a Subaltern and served for a short time in France, but returned to work on the stability of aeroplanes and other aerodynamical problems at Famborough, and continued to work on this kind of problem at various establishments throughout the war, apart from eight months in the United States attached to the British War Mission.

After the war he spent three years as Fellow and Lecturer at Corpus Christi College, Cambridge, and continued his research on physics. He was then appointed Professor of Natural Philosophy (as physics is called in Scotland) at the University of Aberdeen, a post he held for eight years. At Aberdeen he carried out experiments on the behaviour of electrons going through very thin films of metals, which showed that electrons behave as waves in spite of being particles. For this work he later shared the Nobel Prize in Physics with C. J. Davisson of the Bell Telephone Laboratories, who had arrived at the same conclusions by a different kind of experiment. The process of electron diffraction which these experiments established to be possible has been widely used in the investigation of the surfaces of solids.

In the winter of 1929-1930 Thomson visited Cornell University, Ithaca, N.Y. as a << non-resident>> lecturer. In 1930 he was appointed Professor at Imperial College in the University of London; he held this post until 1952, when he became Master of Corpus Christi College, Cambridge, retiring from the latter in 1962.

During his time at Imperial College he became interested in nuclear physics, and when the fission of uranium by neutron was discovered at the beginning of 1939 he was struck by its military and other possibilities, and persuaded the British Air Ministry to procure a ton of uranium oxide for experiments. These experiments were incomplete at the outbreak of war, when Thomson went back to the Royal Aircraft Establishment to work on a series of war problems, including magnetic mines. A year later he was made Chairman of the British Committee set up to investigate the possibilities of atomic bombs. This committee reported in 1941 that a bomb was possible, and Thomson was authorized to give this report to the American scientists Vannevar Bush and James Conant.

He spent the next year as Scientific Liaison Officer at Ottawa, and for part of this time was in close touch with the American atomic bomb effort. On returning to England he was appointed Vice-Chairman of the Radio Board and later became Scientific Adviser to the Air Ministry.

After the war he returned to work at Imperial College, and early in 1946 became interested in the possibilities of nuclear power from deuterium (heavy hydrogen). Some experiments bearing on this were started at Imperial College under Dr. Ware, but Thomson's work was theoretical. Later, because of the requirements of secrecy, this work was transferred to the Associated Electrical Industry's Research Laboratories at Aldermaston, where Thomson continued to act as Consultant.

Sir George Thomson is a Fellow of the Royal Society, and has received the Royal Medal and the Hughes Medal of that Society. He is a Doctor of Science at Cambridge, Hon. D.Sc. (Lisbon), Hon. LL.D. (Aberdeen), Hon. Sc. D. (Dublin), Sheffield, University of Wales and Reading. He has written a book on aerodynamics and other scientific works. His published works also include a popular book on *The Atom* and *The Foreseeable* Future, published in 1955, and *The Inspiration of* Science, published in 1962. He is a Foreign Member of the American Academy of Arts and Sciences and of the Lisbon Academy, and a Corresponding Member of the Austrian Academy.

In 1924 he married Kathleen Buchanan, daughter of the Very Rev. Sir George Adam Smith. They have two sons and two daughters. Ship models form part of his recreations.

Physics 1938

ENRICO FERMI

<<for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons>>

Physics 1938

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

With what we know today of the structure of atoms, we understand perfectly the hopeless task undertaken by alchemists of old, striving to transmute the different elements one to another, and to transform lead and mercury into gold. With the means at their command, they could not work on the essential part of the atom, that is to say the nucleus. The chemical binding forces and most of the physical phenomena, such as radiation, etc., originate in the outermost parts of the atom, in the light, negatively charged electrons orbiting around the nucleus. The characteristic feature of atoms and what makes atoms different from each other, however, is the number of positive unit charges of electricity, or the number of protons, contained in the nucleus. It is this charge which holds together the light, negative electrons that spread, like the planets round the sun, in circular layers round the central nucleus.

At the present level of our knowledge, everything points to the fact that the nuclei of the atoms are composed of particles of two types, one being a heavy particle that has been given the name of *neutron* as it lacks electric charge, and the other being called *proton,* of the same mass as the neutron but with a positive unit charge. A proton is nothing but the nucleus of the lightest atom, i.e. hydrogen. A helium nucleus has two protons and two neutrons; the atom of carbon has six protons and six neutrons, and so on. The atoms are numbered according to the number of protons, or unit charges in the nucleus, with hydrogen as number 1 and uranium as nummer 92, which is the heaviest element known to date.

Meanwhile, it has been found that the nucleus of an atom can contain a number of neutrons less than or in excess of the normal. These atoms, that present the same physical and chemical qualities as the normal atom except that the weight is different, have received the name of *isotopes.* As an example of an -isotope, we can cite the heavy-hydrogen atom discovered by Urey which is a constituent of so-called heavy water. There exist hydrogen isotopes with one or two neutrons in the nucleus.

After all the fruitless attempts at the transmutation of one element into another, the firm conviction grew last century that the different atoms, 92 in number, were indestructible and immutable units of the structure of matter. There was thus great sensation when the Frenchman Becquerel, in 1892, discovered that the element uranium distintegrated giving off strong radiation. Research on this radiation proved that it consisted among others of the helium nuclei that were emitted at very high speed from the uranium atoms. Thus, when one part of the uranium nuclei disintegrates explosively, new substances are formed that disintegrate in their turn, giving off radiations, and so on, until a final stable product is formed which is found to be lead. Among the substances included in this chain, there is the highly radioactive substance radium, which Madame Curie discovered and succeeded in producing. Soon after the radioactivity of uranium was discovered, it was established that this same characteristic occurred in another element, thorium, and later it appeared that this was also the case with the element called actinium. The end-product of the disintegration of these two last-named elements is lead also. However, the lead obtained in these three series is not identical, in so far as the number of constituent neutrons is concerned. The lead that comes from the uranium has 124 neutrons in the nucleus, that which comes from thorium has 126 and that which comes from actinium has 125. So we have three isotopes of lead. Lead as found in nature is usually a mixture of these three types.

It must be noted in this respect that however strong the effect of a substance that is radioactive, it is in many instances only a very small part of the number of atoms that disintegrates. Thus, for a half of the number of uranium atoms to disintegrate, it would take four and a half thousand million years. For radium, the corresponding length of time would be one thousand six hundred years. Other radioactive materials would by contrast only take seconds or days for half of the number of atoms to disintegrate.

As the idea of immutability of the atoms of the elements had to be abandoned, one was back at the age-old problem of the alchemists, the transmutation of the elements. Lord Rutherford was the first to put forward the idea that it would be possible, with the help of the heavy-helium nuclei that are thrown off at great speed by the natural radioactive substances, to split atoms. He met with success in several cases. For the sake of example, we will be content to mention that if a nitrogen nucleus has been struck by the bombarding helium nuclei, a hydrogen nucleus is ejected from the former, and that the rests together with the captured helium nucleus form an oxygen nucleus. By this means helium and nitrogen were thus changed into oxygen and hydrogen. The atom of oxygen that was obtained by this method was however not the ordinary oxygen atom, an atom that has eight neutrons in the nucleus, but an oxygen atom with nine neutrons. This meant that an oxygen isotope had been obtained. This occurs in nature, although rarely; among 12,500 ordinary oxygen atoms, one oxygen isotope is found.

Rutherford's experiments on the splitting of atoms have later been continued by the husband-and-wife team Joliot-Curie, among others, who also used helium nuclei as projectiles. They found that often when new isotopes were formed, these isotopes were radioactive, and distintegrated emitting radioactive radiations. This discovery was of great importance, for it opened up the possibility of obtaining, by artificial processes, substances capable of replacing radium, a material that was both very costly and hard to come by.

Using helium nuclei and also hydrogen nuclei as projectiles, however, one can not split atoms with atomic numbers higher than 20; therefore, only part of the lighter elements of the series of atoms can so be split.

It was granted to today's Nobel Prize winner, Professor Fermi, to succeed in shattering even the heavier and the heaviest elements in the Periodic System.

Fermi used neutrons as projectiles in his experiments.

We have earlier spoken of the neutron as one of the two building-stones in atom nuclei. The existence of the neutron is however only a recent discovery. Rutherford had suspected the existence of a heavy particle without electric charge and had even given it the name neutron; it was given to one of his pupils, Chadwick, to find the neutron in the extremely strong radiation given off by beryllium subjected to the effect of a radioactive substance. The neutron has qualities that make it particularly suitable as a projectile in atomic fission. Both the helium nucleus and the hydrogen nucleus carry electric charges. The strong electric forces of repulsion developed when such a charged particle comes within reach of an atomic nucleus, deflect the projectile. The neutron being uncharged continues on its course without suffering any hindrance until it is stopped by direct impact on a nucleus. As the dimensions of the nuclei are extremely small compared with the distances that separates the different parts of the atoms, such impacts are of rare occurrence. As a result, beams of neutrons, experiment has shown, can pass through armour-plates metres thick without appreciable reduction in speed taking place.

The result which Fermi was able to achieve by using neutron bombardments have proved to be of inestimable value, and have shed new light on the structure of atom nuclei.

At first, the source of radiation was a mixture of beryllium powder and a radioactive substance. Today, neutrons are artifically produced by bombarding beryllium or lithium with heavy-hydrogen nuclei, whereby these substances emit neutrons with high energy. The neutron beams so produced are particularly powerful.

When using neutrons as projectiles, these are captured in the nucleus. In the case of the lighter elements, a hydrogen nucleus or a helium nucleus is ejected instead. With the heavier elements, however, the forces that interlink the atomic parts are so strong that, at least with neutron speeds that can be obtained by present methods, there is no ejection of any material part. The surplus energy disappears in the form of electromagnetic radiations (γ–radiations). As there is no variation in the charge, an isotope is obtained of the initial substance. This isotope, in many cases unstable, disintegrates giving off radioactive radiations. Radioactive materials are thus obtained as a rule.

It was some six months after their first experiment with neutron irradiation that Fermi and his co-workers came by chance on a new discovery which proved to be of the greatest importance. They observed namely that the effect of neutron irradiation was often extremely increased, when the rays were allowed to pass through water or paraffin. Minute study of this phenomenon showed that the speed of the neutrons was slowed down on impact with the hydrogen nuclei which were present in these substances. Contrary to what one had reasons to believe, it appeared that the slow neutrons had a much more powerful effect than the fast neutrons. It was further found that the strongest effect was achieved at a certain speed, which is different for different substances. This phenomenon has therefore been compared with resonance found in optics and acoustics.

With low-speed neutrons, Fermi and his co-workers were successful in producing radioactive isotopes of all the elements with the exception of hydrogen and helium and part of the radioactive substances. More than four hundred new radioactive substances have thus been obtained. A certain number of these has effects stronger than radium as regards radioactivity. Of these substances, more than half were products of bombardment by neutrons. The half-lives of these artificial radioactive substances appear comparatively short, varying from one second to several days.

As we have said, during the irradiation of heavy elements by neutrons, the neutrons are captured and incorporated in the nucleus, and an isotope is thus formed of the primary substance, and this isotope is radioactive. When the isotope decays, however, negative electrons-as can be proved-are projected and new substances are formed with higher positive charges, and therefore substances with higher rank number.

This general pattern that Fermi has found to be the rule when heavy substances are subjected to irradiation by neutrons, took on special interest when applied by him to the last element in the series of elements, viz. uranium, which has rank number 92. Following this process, the first product of disintegration should be an element with 93 positive electric charges and a new element would thus have been found, lying outside the old series. Fermi's researches on uranium made it most probable that a series of new elements could be found, which exist beyond the element up to now held to be the heaviest, namely uranium with rank number 92. Fermi even succeeded in producing two new elements, 93 and 94 in rank number. These new elements he called Ausenium and Hesperium.

Along with Fermi's significant discoveries, and to a certain extent equivalent, can be placed his experimental skill, his brilliant inventiveness and his intuition. These qualities have found expression in the creation of refined research methods which made it possible to demonstrate the existence of these newly formed substances, which occur in extremely small quantities. The same goes for the measurement of the speed at which the different radioactive products disintegrate, particularly since in many cases several disintegration products with different half-lives are simultaneously involved.

Professor Fermi. The Royal Swedish Academy of Sciences has awarded you the Nobel Prize for Physics for 1938 for your discovery of new radioactive substances belonging to the entire field of the elements and for the discovery, which you made in the course of your studies, of the selective powers of the slow neutrons.

We offer our congratulations and we express the most vivid admiration for your brilliant researches, which throw new light on the structure of atomic nuclei and which open up new horizons for the future development of atomic investigation.

We ask you now to receive the Nobel Prize from the hands of His Majesty the King.

ENRICO FERMI

Artifical radioactivity produced by neutron bombardment

Nobel Lecture, December 12, 1938

Although the problem of transmuting chemical elements into each other is much older than a satisfactory definition of the very concept of chemical element, it is well known that the first and most important step towards its solution was made only nineteen years ago by the late Lord Rutherford, who started the method of the nuclear bombardments. He showed on a few examples that, when the nucleus of a light element is struck by a fast a-particle, some disintegration process of the struck nucleus occurs, as a consequence of which the a-particle remains captured inside the nucleus and a different particle, in many cases a proton, is emitted in its place. What remains at the end of the process is a nucleus different from the original one; different in general both in electric charge and in atomic weight.

The nucleus that remains as disintegration product coincides sometimes with one of the stable nuclei, known from the isotopic analysis; very often, however, this is not the case. The product nucleus is then different from all <<naturals nuclei; the reason being that the product nucleus is not stable. It disintegrates further, with a mean life characteristic of the nucleus, by emission of an electric charge (positive or negative), until it finally reaches a stable form. The emission of electrons that follows with a lag in time the first practically instantaneous disintegration, is the so-called artificial radioactivity, and was discovered by Joliot and Irene Curie at the end of the year 1933.

These authors obtained the first cases of artificial radioactivity by bombarding boron, magnesium, and aluminium with a-particles from a polonium source. They produced thus three radioactive isotopes of nitrogen, silicon and phosphorus, and succeeded also in separating chemically the activity from the bulk of the unmodified atoms of the bombarded substance.

The neutron bombardment

Immediately after these discoveries, it appeared that a-particles very likely did not represent the only type of bombarding projectiles for producing artificial radioactivity. I decided therefore to investigate from this point of view the effects of the bombardment with neutrons.

Compared with α-particles, the neutrons have the obvious drawback that the available neutron sources emit only a comparatively small number of neutrons. Indeed neutrons are emitted as products ofnuclear reactions, whose yield is only seldom larger than 10^{-4}. This drawback is, however, compensated by the fact that neutrons, having no electric charge, can reach the nuclei of all atoms, without having to overcome the potential barrier, due to the Coulomb field that surrounds the nucleus. Furthermore, since neutrons practically do not interact with electrons, their range is very long, and the probability of a nuclear collision is correspondingly larger than in the case of the a-particle or the proton bombardment. As a matter of fact, neutrons were already known to be an efficient agent for producing some nuclear disintegrations.

As source of neutrons in these researches I used a small glass bulb containing beryllium powder and radon. With amounts of radon up to 800 millicuries such a source emits about 2×10^7 neutrons per second. This number is of course very small compared to the yield of neutrons that can be obtained from cyclotrons or from high-voltage tubes. The small dimensions, the perfect steadiness and the utmost simplicity are, however, sometimes very useful features of the radon + beryllium sources.

Nuclear reactions produced by neutrons

Since the first experiments, I could prove that the majority of the elements tested became active under the effect of the neutron bombardment. In some cases the decay of the activity with time corresponded to a single mean life; in others to the superposition of more than one exponential decay curve.

A systematic investigation of the behaviour of the elements throughout the Periodic Table was carried out by myself, with the help of several collaborators, namely Amaldi, d'Agostino, Pontecorvo, Rasetti, and Segré. In most cases we performed also a chemical analysis, in order to identify the chemical element that was the carrier of the activity. For short living substances, such an analysis must be performed very quickly, in a time of the order of one minute.

The results of this first survey of the radioactivities produced by neutrons can be summarized as follows: Out of 63 elements investigated, 37 showed an easily detectable activity; the percentage of the activatable elements did not show any marked dependence on the atomic weight of the element. Chemical analysis and other considerations, mainly based on the distribution of the isotopes, permitted further to identify the following three types of nuclear reactions giving rise to artificial radioactivity :

$$^{M}_{Z}A + ^{1}_{0}n = ^{M-3}_{Z-2}A + ^{4}_{2}He \tag{1}$$

$$^{M}_{Z}A + ^{1}_{0}n = {}_{Z-1}^{M}A + ^{1}_{1}H \tag{2}$$

$$^{M}_{Z}A + ^{1}_{0}n = ^{M+1}_{Z}A \tag{3}$$

where $^{M}_{Z}A$ is the symbol for an element with atomic number Z and mass number M; n is the symbol of the neutron.

The reactions of the types (1) and (2) occur chiefly among the light elements, while those of the type (3) are found very often also for heavy elements. In many cases the three processes are found at the same time in a single element. For instance, neutron bombardment of aluminium that has a single isotope ^{27}Al, gives rise to three radioactive products: ^{24}Na, with a half-period of 15 hours by process (1); ^{27}Mg, with a period of IO minutes by process (2); and $^{28}A1$ with a period of 2 to 3 minutes by process (3).

As mentioned before, the heavy elements usually react only according to process (3) and therefore, but for certain complications to be discussed later, and for the case in which the original element has more than one stable isotope, they give rise to an exponentially decaying activity. A very striking exception to this behaviour is found for the activities induced by neutrons in the naturally active elements thorium and uranium. For the investigation of these elements it is necessary to purify first the element as thoroughly as possible from the daughter substances that emit ,&particles. When thus purified, both thorium and uranium emit spontaneously only a-particles, that can be immediately distinguished, by absorption, from the B-activity induced by the neutrons.

Both elements show a rather strong, induced activity when bombarded with neutrons; and in both cases the decay curve of the induced activity shows that several active bodies with different mean lives are produced. We attempted, since the spring of 1934, to isolate chemically the carriers of these activities, with the result that the carriers of some of the activities of uranium are neither isotopes of uranium itself, nor of the elements lighter than uranium down to the atomic number 86. We concluded that the carriers were one or more elements of atomic number larger than 92 ; we, in Rome, use to call the elements 93 and 94 Ausenium and Hesperium respectively. It is known that O. Hahn and L. Meitner have investigated very carefully and extensively the decay products of irradiated uranium, and were able to trace among them elements up to the atomic number 96.*

It should be noticed here, that besides processes (1), (2), and (3) for the production of artificial radioactivity with neutrons, neutrons of sufficiently high energy can react also as follows, as was first shown by Heyn: The primary neutron does not remain bound in the nucleus, but knocks off instead, one of the nuclear neutrons out of the nucleus; the result is a new nucleus, that is isotopic with the original one and has an atomic weight less by one unit. The final result is therefore identical with the products obtained by means of the nuclear photoeffect (Bothe), or by bombardment with fast deuterons. One of the most important results of the comparison of the active products obtained by these processes, is the proof, first given by Bothe, of the existence of isomeric nuclei, analogous to the isomers UX_2 and UZ, recognized long since by O. Hahn in his researches on the uranium family. The number of well-established cases of isomerism appears to increase rather rapidly, as investigation goes on, and represents an attractive field of research.

The slow neutrons

The intensity of the activation as a function of the distance from the neutron source shows in some cases anomalies apparently dependent on the objects that surround the source. A careful investigation of these effects led to the unexpected result that surrounding both source and body to be activated with masses of paraffin, increases in some cases the intensity of activation by a very large factor (up to 100). A similar effect is produced by water, and in general by substances containing a large concentration of hydrogen. Substances not containing hydrogen show sometimes similar features, though extremely less pronounced.

The interpretation of these results was the following. The neutron and the

* The discovery by Hahn and Strassmann of barium among the disintegration products of bombarded uranium, as a consequence of a process in which uranium splits into two approximately equal parts, makes it necessary to reexamine all the problems of the transuranic elements, as many of them might be found to be products of a splitting of uranium.

proton having approximately the same mass, any elastic impact of a fast neutron against a proton initially at rest, gives rise to a distribution of the available kinetic energy between neutron and proton; it can be shown that a neutron having an initial energy of 10^6 volts, after about 20 impacts against hydrogen atoms has its energy already reduced to a value close to that corresponding to thermal agitation. It follows that, when neutrons of high energy are shot by a source inside a large mass of paraffin or water, they very rapidly lose most of their energy and are transformed into <<slow neutrons>>. Both theory and experiment show that certain types of neutron reactions, and especially those of type (3), occur with a much larger cross-section for slow neutrons than for fast neutrons, thus accounting for the larger intensities of activation observed when irradiation is performed inside a large mass of paraffin or water.

It should be remarked furthermore that the mean free path for the elastic collisions of neutrons against hydrogen atoms in paraffin, decreases rather pronouncedly with the energy. When therefore, after three or four impacts, the energy of the neutron is already considerably reduced, its probability of diffusing outside of the paraffin, before the process of slowing down is completed, becomes very small.

To the large cross-section for the capture of slow neutrons by several atoms, there must obviously correspond a very strong absorption of these atoms for the slow neutrons. We investigated systematically such absorptions, and found that the behaviour of different elements in this respect is widely different; the cross-section for the capture of slow neutrons varies, with no apparent regularity for different elements, from about 10^{-24} cm^2 or less, to about a thousand times as much. Before discussing this point, as well as the dependence of the capture cross-section on the energy of the neutrons we shall first consider how far down the energy of the primary neutrons can be reduced by the collisions against the protons.

The thermal neutrons

If the neutrons could go on indefinitely diffusing inside the paraffin, their energy would evidently reach finally a mean value equal to that of thermal agitation. It is possible, however, that, before the neutrons have reached this lowest limit of energy, either they escape by diffusion out of the paraffin, or are captured by some nucleus. If the neutron energy reaches the thermal value, one should expect the intensity of the activation by slow neutrons to depend upon the temperature of the paraffin.

Soon after the discovery of the slow neutrons, we attempted to find a temperature dependence of the activation, but, owing to insufficient accuracy, we did not succeed. That the activation intensities depend upon the temperature was proved some months later by Moon and Tillman in London; as they showed, there is a considerable increase in the activation of several detectors, when the paraffin, in which the neutrons are slowed down, is cooled from room temperature to liquid-air temperature. This experiment defi nitely proves that a considerable percentage of the neutrons actually reaches the energy of thermal agitation. Another consequence is that the diffusion process must go on inside the paraffin for a relatively long time.

In order to measure, directly at least, the order of magnitude of this time, an experiment was attempted by myself and my collaborators. The source of neutrons was fastened at the edge of a rotating wheel, and two identical detectors were placed on the same edge, at equal distances from the source, one in front and one behind with respect to the sense of rotation. The wheel was then spun at a very high speed inside a fissure in a large paraffin block. We found that, while, with the wheel at rest, the two detectors became equally active, when the wheel was in motion during the activation, the detector that was behind the source became considerably more active than the one in front. From a discussion of this experiment was deduced, that the neutrons remain inside the paraffin for a time of the order of 10^{-4} seconds.

Other mechanical experiments with different arrangements were performed in several laboratories. For instance Dunning, Fink, Mitchell, Pegram, and Segré: in New York, built a mechanical velocity selector, and proved by direct measurement, that a large amount of the neutrons diffusing outside of a block of paraffin, have actually a velocity corresponding to thermal agitation.

After their energy is reduced to a value corresponding to thermal agitation, the neutrons go on diffusing without further change of their average energy. The investigation of this diffusion process, by Amaldi and myself, showed that thermal neutrons in paraffin or water can diffuse for a number of paths of the order of 100 before being captured. Since, however, the mean free path of the thermal neutrons in paraffin is very short (about 0.3 cm) the total displacement of the thermal neutrons during this diffusion process is rather small (of the order of 2 or 3 cm). The diffusion ends when the thermal neutron is captured, generally by one of the protons, with production of a deuteron. The order of magnitude for this capture probability can be calculated, in good agreement with the experimental value, on the assumption that the transition from a free-neutron state to the state in which the neutron is bound in the deuteron is due to the magnetic dipole moments of the proton and the neutron. The binding energy set free in this process, is emitted in the form of γ-rays, as first observed by Lea.

All the processes of capture of slow neutrons by any nucleus are generally accompanied by the emission of γ-rays : Immediately after the capture of the neutron, the nucleus remains in a state of high excitation and emits one or more y-quanta, before reaching the ground state. The y-rays emitted by this process were investigated by Rasetti and by Fleischmann.

Absorption anomalies

A theoretical discussion of the probability of capture of a neutron by a nucleus, under the assumption that the energy of the neutron is small compared with the differences between neighbouring energy levels in the nucleus, leads to the result that the cross-section for the capture process should be inversely proportional to the velocity of the neutron. While this result is in qualitative agreement with the high efficiency of the slow-neutron bombardment observed experimentally, it fails on the other hand to account for several features of the absorption process, that we are now going to discuss.

If the capture probability of a neutron were inversely proportional to its velocity, one would expect two different elements to behave in exactly the same way as absorbers of the slow neutrons, provided the thicknesses of the two absorbers were conveniently chosen, so as to have equal absorption for neutrons of a given energy. That the absorption obeys instead more complicated laws, was soon observed by Moon and Tillman and other authors who showed that the absorption by a given element appears, as a rule, to be larger when the slow neutrons are detected by means of the activity induced in the same element. That the simple law of inverse proportionality does not hold, was also proved by a direct mechanical experiment by Dunning, Pegram, Rasetti, and others in New York.

In the winter of 1935-1936 a systematic investigation of these phenomena was carried out by Amaldi and myself The result was, that each absorber of the slow neutrons has one or more characteristic absorption bands, usually for energies below 100 volts. Besides this or these absorption bands, the absorption coefficient is always large also for neutrons of thermal energy. Some elements, especially cadmium, have their characteristic absorption band overlapping with the absorption in the thermal region. This element absorbs therefore very strongly the thermal neutrons, while it is almost transparent to neutrons of higher energies. A thin cadmium sheet is therefore used for filtering the thermal neutrons out of the complex radiation that comes out of a paraffin block containing a neutron source inside.

Bohr and Breit and Wigner proposed independently to explain the above anomalies, as due to resonance with a virtual energy level of the compound nucleus (i.e. the nucleus composed of the bombarded nucleus and the neutron). Bohr went much farther in giving also a qualitative explanation of the large probability for the existence of at least one such level, within an energy interval of the order of magnitide of 100 volts corresponding to the energy band of the slow neutrons. This band corresponds, however, to an excitation energy of the compound nucleus of many million volts, representing the binding energy of the neutron. Bohr could show that, since nuclei, and especially heavy nuclei, are systems with a very large number of degrees of freedom, the spacing between neighbouring energy levels decreases very rapidly with increasing excitation energy. An evaluation of this spacing shows that whereas for low excitation energies the spacing is of the order of magnitude of 10^5 volts, for high excitation energies, of the order of ten million volts, it is reduced (for elements of mean atomic weight) to less than one volt. It is therefore a very plausible assumption that one (or more) such level lies within the slow-neutron band, thus explaining the large frequency of the cases in which absorption anomalies are observed.

Before concluding this review of the work on artificial radioactivity produced by neutrons, I feel it as a duty to thank all those who have contributed to the success of these researches. I must thank in particular all my collaborators that have already been mentioned; the Istituto di Sanità Pubblica in Rome and especially Prof. G. C. Trabacchi, for the supply of all the many radon sources that have been used; the Consiglio Nazionale delle Richerche for several grants.

Biography

Enrico Fermi was born in Rome on 29th September, 1901, the son of Alberto Fermi, a Chief Inspector of the Ministry of Communications, and Ida de Gattis. He attended a local grammar school, and his early aptitude for mathematics and physics was recognized and encouraged by his father's colleagues, among whom A. Amidei. In 1918, he won a fellowship of the Scuola Normale Superiore of Pisa. He spent four years at the University of Piss, gaining his doctor's degree in physics in 1922 with Professor Puccianti.

Soon afterwards, in 1923, he was awarded a scholarship from the Italian Government and spent some months with Professor Max Born in Göttingen. With a Rockefeller Fellowship, in 1924, he moved to Leyden to work with P. Ehrenfest, and later that same year he returned to Italy to occupy for two years (1924-1926) the post of Lecturer in Mathematical Physics and Mechanics at the University of Florence.

In 1926, Fermi discovered the statistical laws, nowadays known as the <<Fermi statistics>>, governing the particles subject to Pauli's exclusion principle (now referred to as <<fermions>>, in contrast with <<bosons>> which obey the Bose-Einstein statistics).

In 1927, Fermi was elected Professor of Theoretical Physics at the University of Rome (a post which he retained until 1938, when he - immediately after the receipt of the Nobel Prize - emigrated to America, primarily to escape Mussolini's fascist dictatorship).

During the early years of his career in Rome he occupied himself with electrodynamic problems and with theoretical investigations on various spectroscopic phenomena. But a capital turning-point came when he directed his attention from the outer electrons towards the atomic nucleus itself. In 1934, he evolved the b- decay theory, coalescing previous work on radiation theory with Pauli's idea of the neutrino. Following the discovery by Curie and Joliot of artificial radioactivity (1934), he demonstrated that nuclear transformation occurs in almost every element subjected to neutron bombardment. This work resulted in the discovery of slow neutrons that same year, leading to the discovery of nuclear fission and the production of elements lying beyond what was until then the Periodic Table.

In 1938, Fermi was without doubt the greatest expert on neutrons, and he continued his work on this topic on his arrival in the United States, where he was soon appointed Professor of Physics at Columbia University, N.Y. (1939-1942).

Upon the discovery of fission, by Hahn and Strassmann early in 1939, he immediately saw the possibility of emission of secondary neutrons and of a chain reaction. He proceeded to work with tremendous enthusiasm, and directed a classical series of experiments which ultimately led to the atomic pile and the first controlled nuclear chain reaction. This took place in Chicago on December 2, 1942 - on a volley-ball field situated beneath Chicago's stadium. He subsequently played an important part in solving the problems connected with the development of the first atomic bomb (He was one of the leaders of the team of physicists on the Manhattan Project for the development of nuclear energy and the atomic bomb.)

In 1944, Fermi became American citizen, and at the end of the war (1946) he accepted a professorship at the Institute for Nuclear Studies of the University of Chicago, a position which he held until his untimely death in 1954. There he turned his attention to high-energy physics, and led investigations into the pion-nucleon interaction.

During the last years of his life Fermi occupied himself with the problem of the mysterious origin of cosmic rays, thereby developing a theory, according to which a universal magnetic field - acting as a giant accelerator - would account for the fantastic energies present in the cosmic ray particles.

Professor Fermi was the author of numerous papers both in theoretical and experimental physics. His most important contributions were:
<<Sulla quantizzazione de1 gas perfetto monoatomico>>, Rend. *Accad. Naz. Lincei*, 1935 (also in Z. *Phys.*, 1936), concerning the foundations of the statistics of the electronic gas and of the gases made of particles that obey the Pauli Principle.

Several papers published in Rend. *Accad. Naz. Lincei, 1927-28,* deal with the statistical model of the atom (Thomas-Fermi atom model) and give a semiquantitative method for the calculation of atomic properties. A resume of this work was published by Fermi in the volume: *Quantentheorie und Chemie,* edited by H. Falkenhagen, Leipzig, 1928.

<<Über die magnetischen Momente der Atomkerne>>, Z. *Phys.*, 1930, is a quantitative theory of the hyperfine structures of spectrum lines. The magnetic moments of some nuclei are deduced therefrom.

<< Tentativo di una teoria dei raggi b >>, *Ricerca Scientifica,* 1933 (also Z. *Phys.,* 1934) proposes a theory of the emission of b- rays, based on the hypothesis, first proposed by Pauli, of the existence of the neutrino.

The Nobel Prize for Physics was awarded to Fermi for his work on the artificial radioactivity produced by neutrons, and for nuclear reactions brought about by slow neutrons. The first paper on this subject <<Radio-attività indotta da1 bombardamento di neutroni>> was published by him in *Ricerca Scientifica,* 1934. All the work is collected in the following papers by himself and various collaborators : <<Artificial radioactivity produced by neutron bombardment>>, *Proc. Roy. Soc.,* 1934 and 1935; <<On the absorption and diffusion of slow neutrons>>, *Phys. Rev.,* 1936. The theoretical problems connected with the neutron are discussed by Fermi in the paper <<Sul moto dei neutroni lentia>>, *Ricerca Scientifica,* 1936.

His *Collected Papers* are being published by a Committee under the Chairmanship of his friend and former pupil, Professor E. Segré: (Nobel Prize winner 1959, with O. Chamberlain, for the discovery of the antiproton).

Fermi was member of several academies and learned societies in Italy and abroad (he was early in his career, in 1929, chosen among the first 30 members of the Royal Academy of Italy).

As lecturer he was always in great demand (he has also given several courses at the University of Michigan, Ann Arbor; and Stanford University, Calif). He was the first recipient of a special award of $50,000 - which now bears his name - for work on the atom.

Professor Fermi married Laura Capon in 1928. They had one son Giulio and one daughter Nella. His favourite pastimes were walking, mountaineering, and winter sports.

He died in Chicago on 29th November, 1954.

Physics 1939

ERNEST ORLANDO LAWRENCE

<<for the invention ad development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements>>

Physics 1939

The following account of Lawrence's work is by Professor K. M. G. Siegbahn, member of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

In 1919 Lord Rutherford discovered that nitrogen can be brought to emit protons by bombardment with alpha particles, according to the nuclear-reaction equation :

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

This discovery meant the initiation of a new era in natural sciences. However, as long as one was limited to the use of alpha radiation of naturally radioactive substances for carrying out nuclear reactions, very strict limits were set to further development both with regard to the substances which could produce these reactions, as well as to the quantitative yield of the reactions.

How then would it be possible, by some method other than the use of radioactive substances, to make available projectiles with sufficient energies to bring about nuclear reactions in an artificial way? Fortunately, the quantum-mechanical treatment of this problem, developed in the meantime, implied that the energy of the particles need not be as high as might be expected from classical theories. Among all the proposals and experiments carried out in different quarters to produce sufficiently fast particles for nuclear experiments, those carried out at the Cavendish Laboratory on Rutherford's initiative were the first to yield a positive result (1932). In this case use was made of a high electrical voltage, up to about 600 kV, to accelerate protons which, upon bombarding lithium, caused a nuclear reaction:

$$^{7}_{3}\mathrm{Li} + ^{1}_{1}\mathrm{H} \rightarrow 2\ ^{4}_{2}\mathrm{He}$$

Two years earlier (September, 1930), however, Lawrence had indicated an entirely new method to obtain fast particles, i.e. the so-called magnetic resonance acceleration. This method is based on a brilliant combination of a constant homogeneous magnetic field and an oscillating electrical field with constant frequency, whereby the ions move about in circular orbits with ever-increasing radii, through stepwise acceleration. The communication on the first simple experimental model of the <<*cyclotron*>. was published in the same year as the aforementioned experiment with artificially produced nuclear reactions at the Cavendish Laboratory. Under Lawrence's guidance and with the assistance of a large number of skilled collaborators the cyclotron method soon proved suitable for rapid development towards an exceptionally effective tool for research in this field. The energies of the particles, successively obtained by the further development of the cyclotron method, surpassed significantly that which had been obtained by other means. The maximum energy of the particles accelerated in the cyclotron even considerably exceeded the energy values present in alpha rays of naturally radioactive substances. While the latter energy is of the order of magnitude of 7 to 8 MeV, the energy of alpha particles supplied by the cyclotron is, according to latest reports (November, 1939), up to 38 MeV.

Experiments with heavy hydrogen nuclei as projectiles, with which Lawrence and his collaborators could produce nuclear reactions with practically all elements, proved to be particularly successful.

With regard to the intensities of the radiation produced in the cyclotron, it can be mentioned that a current of over 150 microamperes has been attained, corresponding to the alpha radiation of *30 kg radium.* As a comparison it may be mentioned that the entire world stock of purified radium can be estimated at 1 kg.

With the powerful means given to nuclear research by the cyclotron, an explosive development took place in this field. Nowadays, cyclotron installations are built or planned in a large number of laboratories throughout the world. The number of publications on the results obtained with the use of cyclotrons has grown with the speed of an avalanche.

The greatest significance the cyclotron has had is in the production of artificially radioactive substances. True, the discovery of active isotopes was made by the Curie-Joliots in 1933 with the use of alpha particles from naturally radioactive substances, but only with the cyclotron was it possible to produce active isotopes in large quantities. This was, among other things, an essentialcondition for the use of active elements for biological and medical purposes. On this terrain, where such splendid achievements had already been made, a new field for research and practical applications has been opened, thanks to the cyclotron. To appreciate the strength of the radioactive sources produced for the last-mentioned purposes, the following data may be given. Using deuterium in his cyclotron Lawrence was able, already in 1936, to produce daily quantities of *active sodium,* which, with regard to gamma radiation, were equivalent to 200 mg radium. The later cyclotrons of larger dimensions (1939) have a production capacity of about 10 times this value.

Finally, it may be mentioned that the cyclotron offers possibilities of producing neutron radiation of great intensity, as a result of which quantitative research on the physical and biological effects of this radiation has been carried out. With regard to therapeutic applications, these preliminary investigations are rather encouraging.

Within the history of the development of experimental physics, the cyclotron takes an exceptional position. It is, without comparison, the most extensive and complicated apparatus construction carried out so far. As to the scientific results achieved, we can scarcely find anything similar among the other experimental tools in physics. It is also evident that the operation and testing of an apparatus of this type, with such a multitude of details, cannot be the merit of one man alone. As promotor and leader of this almost gigantic work, Lawrence has shown such merits in the field of physics that the Royal Swedish Academy of Sciences has considered him as having fulfilled to the highest degree the requirements implied in the award of the Nobel Prize*.

* Owing to the war conditions, the Prize was handed over to Professor Lawrence at a ceremony in Berkeley on February 29, 1940. Among the speeches delivered was a thorough account of Professor Lawrence's work by the physicist R. T. Birge. A report of the ceremonies in Berkeley has been published in <<Les Prix Nobel en 1939>>, Stockholm,1942.

ERNEST O. LAWRENCE

The evolution of the cyclotron

Nobel Lecture, December 11, 1931

The development of the cyclotron was begun more than twenty years ago and perhaps it is appropriate on this occasion to give something of an historical account. The story goes back to 1928 when I had the good fortune of becoming a member of the Faculty of the University of California. At that time it seemed opportune to review my plans for research, to see whether I might not profitably go into nuclear research, for the pioneer work of Rutherford and his school had clearly indicated that the next great frontier for the experimental physicist was surely the atomic nucleus.

It seemed equally obvious also at that time that a prerequisite to a successful experimental attack on the nucleus was the development of means of accelerating charged particles to high velocities-to energies measured in millions of electron volts, a task which appeared formidable indeed! Accordingly, I devoted considerable time and thought to the technical problem of ways and means of reaching millions of electron volts in the laboratory. The problem seemed to reduce itself to two parts, *(a)* the production of high voltages, and *(b)* the development of accelerating tubes capable of withstanding such high voltages.

Since transformers and rectifiers for such high voltages seemed rather out of the question for various reasons, not the least of which were connected with financial limitations, I naturally looked for alternative means of producing high voltages: the surge generator which was used by Brasch and Lange; the electrostatic generator which Professor W. F. G. Swarm was working on when I was a student under him at the University of Minnesota in 1924 and which was later brought to practical development by Van de Graaff; and the Tesla coil source of high voltage which Tuve, Breit, and Hafstad brought to a fruitful stage of development.

One evening early in 1929 as I was glancing over current periodicals in the University library, I came across an article in a German electrical engineering journal by Wideröe on the multiple acceleration of positive ions. Not being able to read German easily, I merely looked at the diagrams and photographs of Wideröe's apparatus and from the various figures in the article was able to determine his general approach to the problem -i.e. the multiple acceleration of the positive ions by appropriate application of radio-frequency oscillating voltages to a series of cylindrical electrodes in line. This new idea immediately impressed me as the real answer which I had been looking for to the technical problem of accelerating positive ions, and without looking at the article further I then and there made estimates of the general features of a linear accelerator for protons in the energy range above one million volt electrons. Simple calculations showed that the accelerator tube would be some meters in length which at that time seemed rather awkwardly long for laboratory purposes. And accordingly, I asked myself the question, instead of using a large number of cylindrical electrodes in line, might it not be possible to use two electrodes over and over again by sending the positive ions back and forth through the electrodes by some sort of appropriate magnetic field arrangement. Again a little analysis of the problem showed that a uniform magnetic field had just the right properties -that the angular velocity of the ions circulating in the field would be independent of their energy so that they would circulate back and forth between suitable hollow electrodes in resonance with an oscillating electrical field of a certain frequency which now has come to be known as the <<cyclotron frequency>>.

Now this occasion affords me a felicitous opportunity in some measure to correct an error and an injustice. For at that time I did not carefully read Wideröe's article and note that he had gotten the idea of multiple accelera-

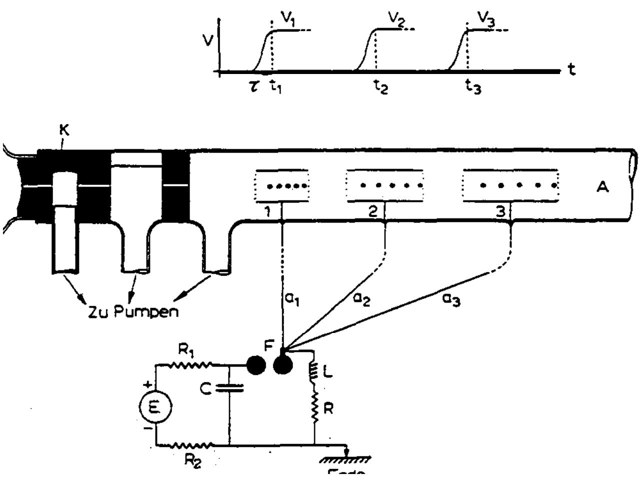

Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

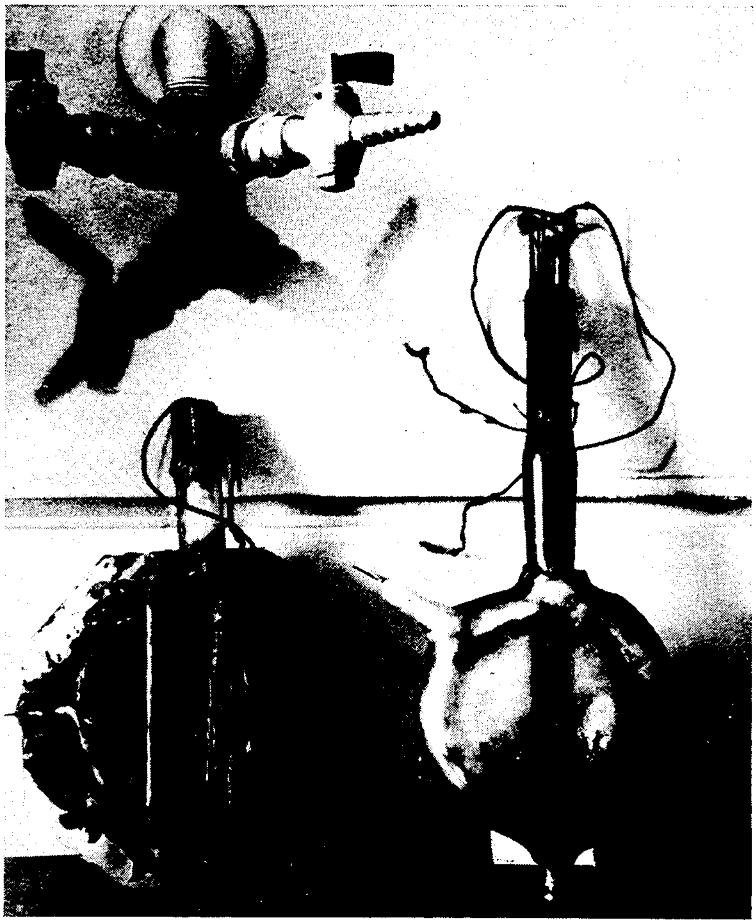

Fig. 2. First crude models of the cyclotron constructed by Edefsen in 1930.

tion of ions from one of your distinguished colleagues, Professor G. Ising, who in 1924 published this important principle. It was only after several years had passed that I became aware of Professor Ising's prime contribution. I should like to take this opportunity to pay tribute to his work for he surely is the father of the developments of the methods of multiple acceleration.

Perhaps you will permit me first of all to show a slide of the diagram of the linear accelerator in his original publication (Fig. 1).

I hope I have not belabored excessively these early incidents of history and now I should like to trace rapidly the evolution of the cyclotron by showing examples of the apparatus in our laboratory as it was developed in the course of time. In doing so, I am afraid I shall not be able to mention all those who

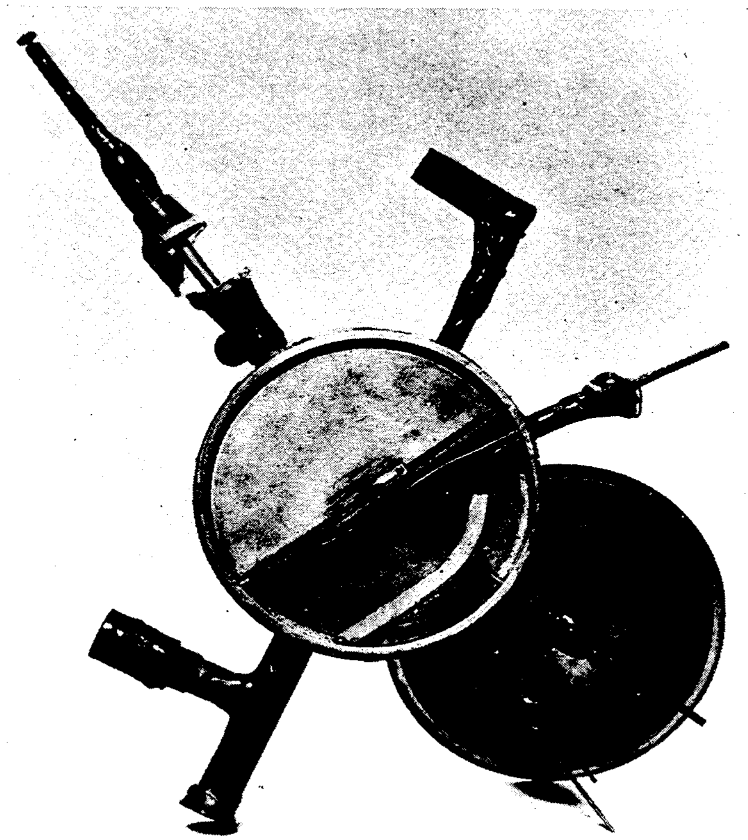

Fig. 3. Working model of cyclotron constructed by M. Stanley Livingston which pointed the way to later developments.

deserve great credit for the developments - as from the beginning the work has been a team effort involving many able and devoted co-workers in many laboratories. As I am sure you will appreciate, a great many diverse talents are involved in such developments and whatever measure of success is achieved is dependent on close and effective collaboration.

Although the cyclotron was, so to speak, invented early in 1929, actual experimental work on its development was begun in the spring of 1930 when one of my students, Nels Edlefsen, constructed two crude models shown in Fig. 2. One of the models which gave slight evidence of working consisted of two copper duants waxed together on a glass plate with a filament source along the diameter at the center much like later models.

In the fall, another student, M. Stanley Livingston, continued the development and quickly constructed the model shown in Fig. 3 which, as you see, had all the features of early cyclotrons and which worked very well indeed as 80,000 volt protons were produced with less than 1,000 volts on the semi-circular accelerating electrode - now called the <<dee>>.

The next milestone in the development was the construction of a larger model (Figs. 4 and 5) which produced protons of the desired energies -in the region of one million electron volts. Livingston and I had the remarkable good fortune of observing that this apparatus was rather more successful than we had expected. For, as you can well imagine, we were concerned about how many of the protons would succeed in spiralling around a great many times without getting lost on the way. We soon recognized that the focussing actions of the electric and magnetic fields were responsible for the relatively large currents of protons that reached the periphery of the apparatus; but we must acknowledge that here again experiment preceded theory!

We were busy with further improvements of the apparatus to produce larger currents at higher voltages when we received word of the discovery by Cockcroft and Walton, which this year has been recognized by the Nobel Prize in Physics. We were overjoyed with this news, for it constituted definite assurance that the acceleration of charged particles to high speeds was a worth-while endeavor. As you can imagine, we went ahead with all speed, and it was not long before the disintegration of lithium by protons had been observed with the apparatus.

Now we may proceed rapidly with examples of later developments. Figs. 6 and 7 show the first two-dee 27" cyclotron which produced protons and deuterons of several million volts and was used extensively in early investigations of nuclear reactions involving neutrons and artificial radioactivity.

Again, with this apparatus the discoveries of Chadwick and the Curie-Joliots were promptly confirmed. Indeed, looking back it is remarkable that we managed to avoid the discovery of artificial radioactivity prior to their epoch-making announcement: for we tried at first to use Geiger counters in observing nuclear radiations produced by the cyclotron and observed that their background was always variable and large. In those days Geiger counters had the reputation of being unreliable and, rather than looking into the matter of their apparent misbehavior, we turned to ion chambers and linear amplifiers to. observe heavy-particle nuclear reactions. Of course, the Geiger counters were simply being faithful to duty and recording the radiations from the artificial radioactive substances, and this became immediately ap-

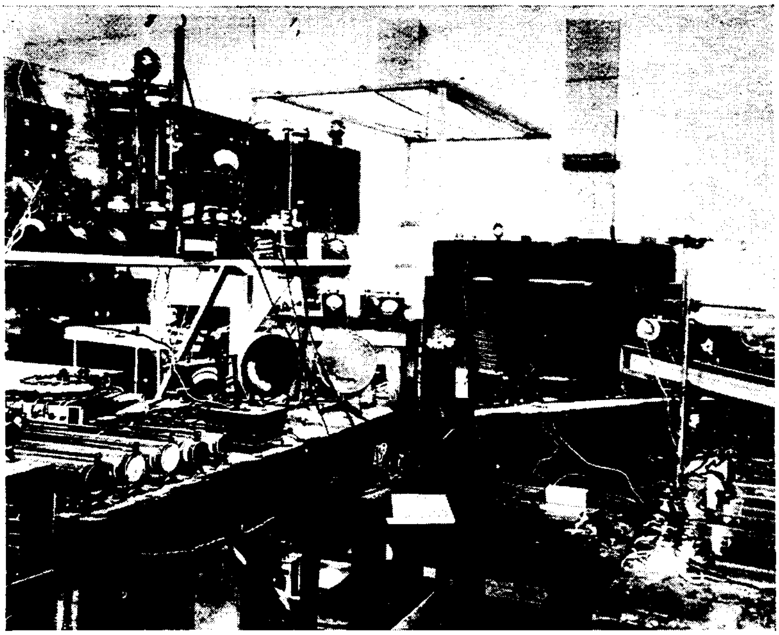

Fig. 4. General view of first cyclotron used in nuclear transformations.

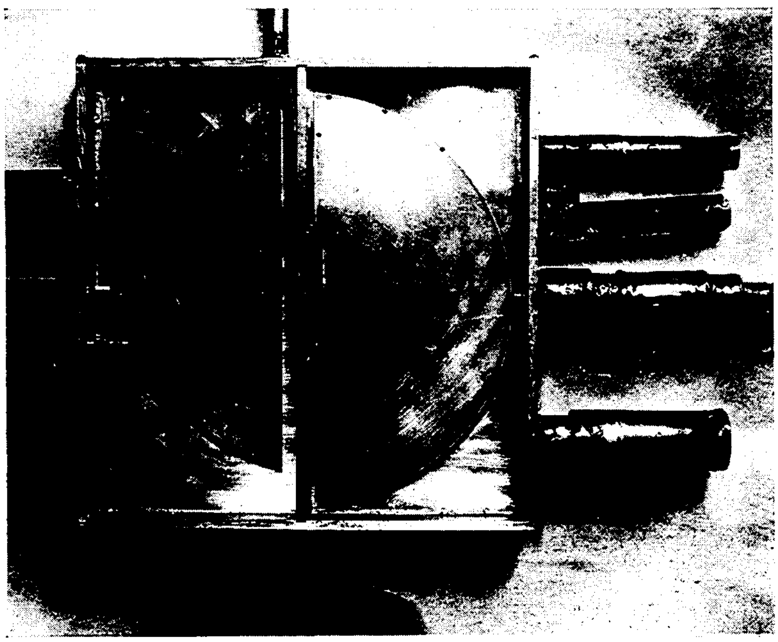

Fig. 5. Vacuum chamber ofcyclotron (Fig. 4) which produced 1 million volt protons.

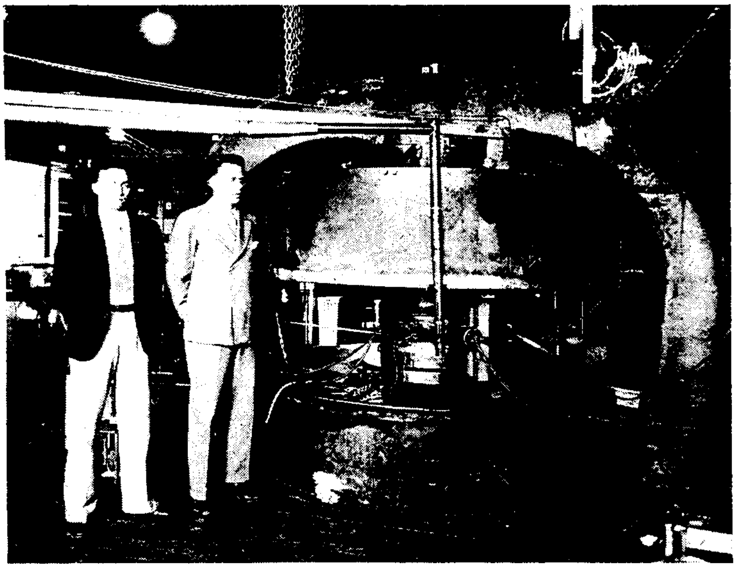

Fig. 6. General view of 27" cyclotron built by young physicists including M.S. Livingston (left) and E. O. Lawrence *(right).* (The lack of good engineering design is quite evident!)

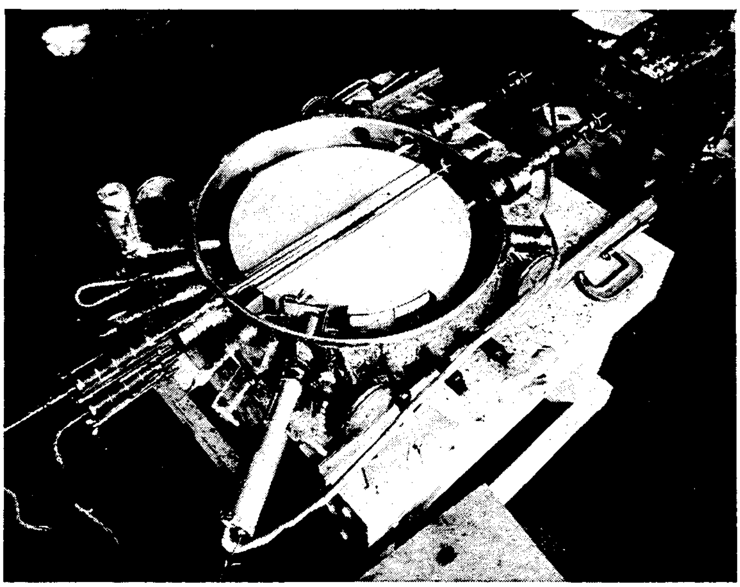

Fig. 7. The chamber of the 27" cyclotron showing two dees.

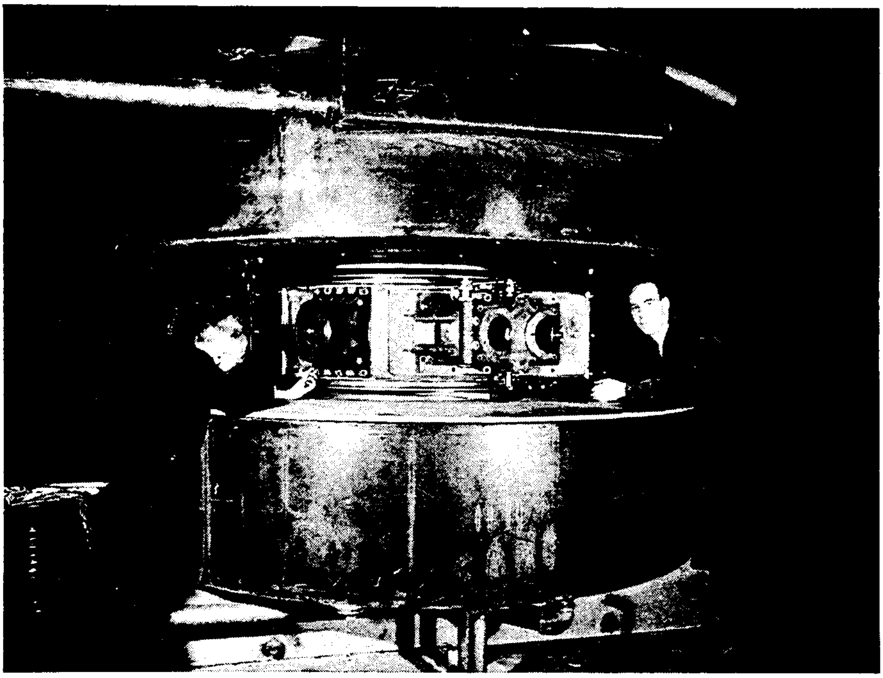

Fig. 8. Early photograph of 60" cyclotron showing first evidence of good engineering practice, introduced into our laboratory by W. M. Brobeck *(right)* and Donald Cooksey *(left)*.

parent after the Curie-Joliot announcement. Again, we were overjoyed at the richness of the domain in the nucleus accessible to particles of several million electron volts energy and there followed a happy period of intensive experimental investigations, which indeed through the years has gained ever-increasing tempo in laboratories the world over.

The next milestone in our laboratory was the construction of the 60" cyclotron, and this undertaking was greatly strengthened by the joining of our team of William Brobeck, a truly outstanding engineer. Brobeck brought to our laboratory sound engineering practice which from the day he joined us has had a profound effect on developments. To him, more than to any other one individual, goes the credit for the success of the 60" cyclotron and all subsequent developments. As you can see in Fig. 8, the cyclotron for the first time began to look like a well-engineered machine. It was with this machine that the discoveries of the transuranium elements were made which have been rewarded this year by the award of the Nobel Prize in Chemistry to McMillan and Seaborg. Perhaps the finest example of a 60" cyclotron is now in operation at the Nobel Institute here in Stockholm.

Soon our objective was the production of protons and deuterons of much higher energies, and Bethe pointed out the difficulty introduced by the relativistic increase in mass of the particles as they increase in energy in the course of acceleration which causes them to get out of resonance with an oscillating electric field in a uniform magnetic field.

However, Thomas devised a magnetic field that avoided the limitation discussed by Bethe, and also, of course, it was recognized that one might modulate the frequency in step with the changing angular frequency of the accelerated particles. These two solutions of the technical problem of yet higher energies - the region of 100 million volts -seemed impractical; at least much less practicable than simply so designing the cyclotron that a million volts or more could be applied to the dees, so that the particles would need to circulate around relatively few times in reaching the desired high energies.

Accordingly, just before the war, Brobeck and co-workers designed the great 184" cyclotron shown in Fig. 9.

As is well known, the war prevented the building of this machine and immediately afterwards McMillan, and Veksler independently a few months earlier, came forward with the principle of phase stability which transformed the conventional cyclotron to a much more powerful instrument for higher energies -the synchrocyclotron. Fig. IO shows the main features of the Berkeley 184" synchrocyclotron which produces 340 MeV protons, while there are later and more modern installations, notably at Columbia University and University of Chicago, which produce somewhat higher energies. As I am sure this audience is well aware, a beautifully engineered synchrocyclotron is nearing completion at Uppsala.

On completion of the 184" synchrocyclotron, it was natural that Brobeck should turn his attention to the engineering problem of applying the synchrotron principle to the acceleration of heavy ions, particularly protons, *to* much higher energies-in the range of billions of electron volts. It was not long before his engineering studies indicated the practicability of producing protons in the energy range well above one billion electron volts.

With the extensive developments in the atomic energy field, large funds became available for research purposes - much larger than seemed possible before the war - and indeed, as soon as all concerned were convinced of the practicality ofbuilding a proton synchrotron for several billion electron volts, the construction of two installations was begun, one at Brookhaven for

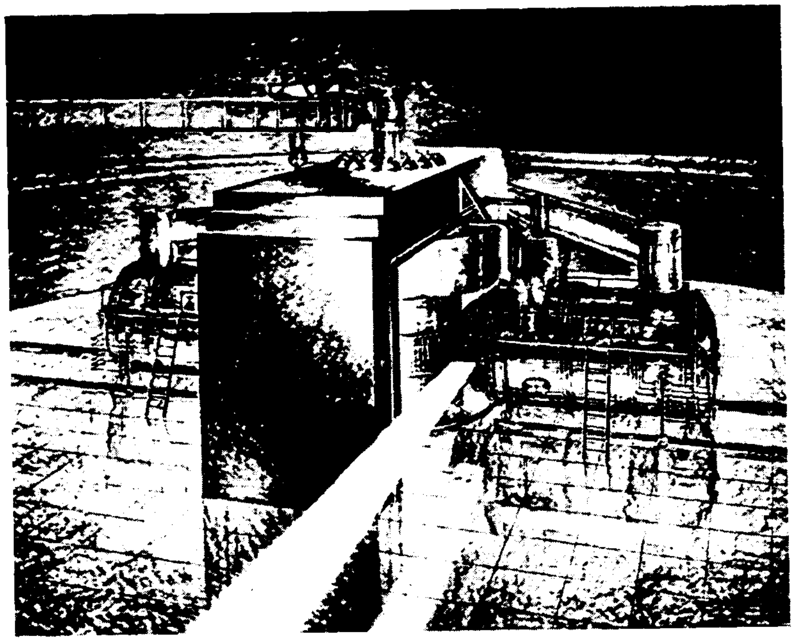

Fig. 9. Artist's sketch of 184" cyclotron designed by Brobeck before the war to produce 100 million electron volt protons.

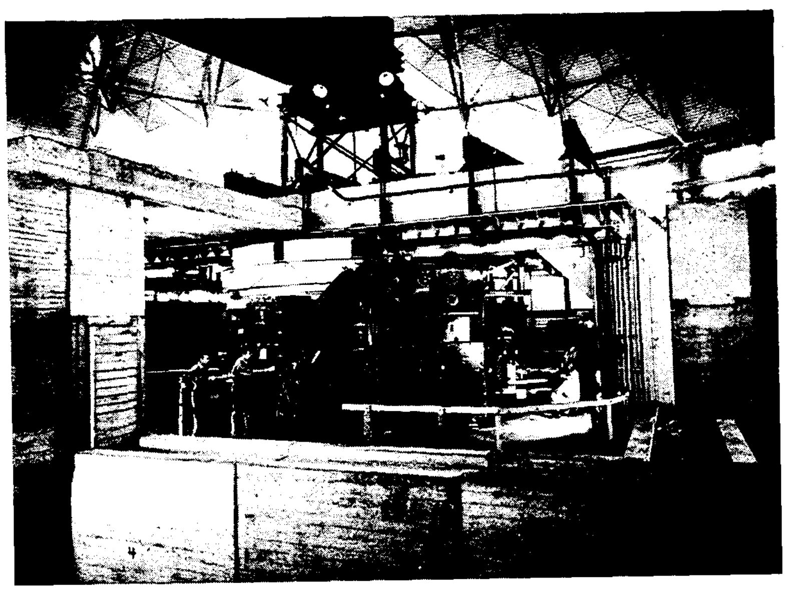

Fig. 10. General view of 184" synchrocyclotron which produces 340 MeV protons. (The concrete shielding, partially removed in this photograph, is 15' in thickness.)

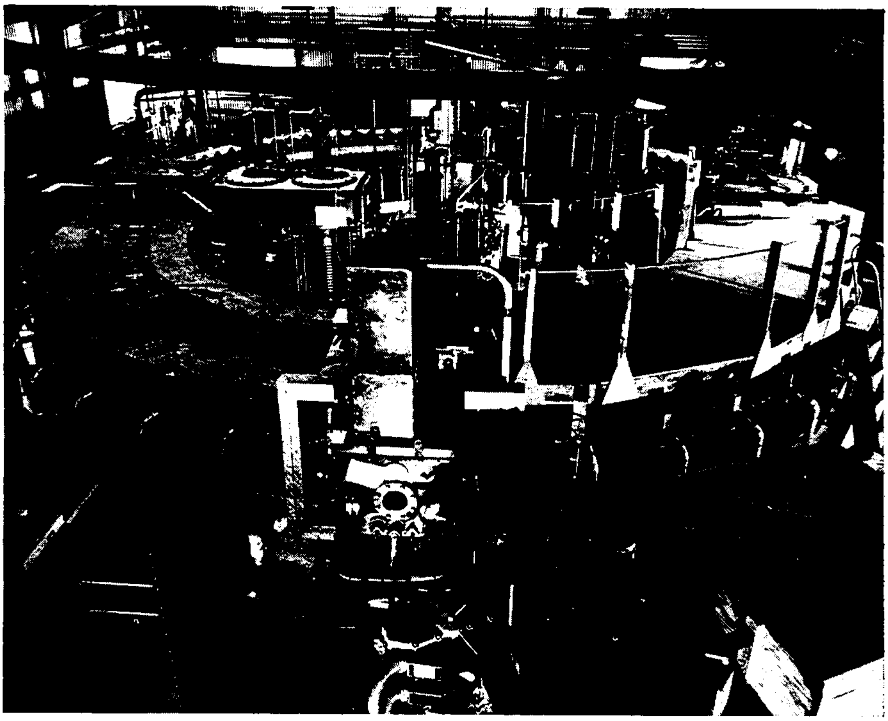

Fig. 11. One-quarter scale operating model of 6 BeV proton synchrotron.

about 3 billion electron volts and a second at Berkeley for about twice this energy.

The first step in these large undertakings was to build a substantial operating model to test out the theory of the proton synchrotron, as well as the engineering principles of design. Accordingly, a quarter-scale operating model was constructed and is shown in Fig. II. A small cyclotron was designed to produce large current pulses of I MeV protons which were injected into the <<race track>> of the synchrotron by an appropriate magnetic and electrostatic deflecting system which can be seen in the foreground of Fig. 11. This model worked as expected and provided a great deal of practical data giving confidence that the full-scale machines will function successfully and satisfactorily.

It is hardly appropriate here to describe either the Brookhaven or Berkeley proton synchrotrons (the former is called the *cosmotron* and the latter is called the *bevatron)* but perhaps it is of interest to show a number of photographs which display the general features of this great machine (Figs. 12, 13, 14, 15 and 16).

Now that we shall soon have 5 or 10 BeV particles in the laboratory, what possibilities are there for going on higher to 50 or 100 BeV? One answer is that the limitation of the bevatron is largely a financial one. With a correspondingly larger expenditure, higher energies surely can be reached.

But I should like to close by emphasizing that a more feasible, if not more interesting, approach to the problem of higher-energy nuclear projectiles is the acceleration of multiply charged heavier ions such as C^{6+}, or Ne^{10+} Already extraordinarily interesting nuclear reactions have been produced by the acceleration of C^{6+} ions to 120 MeV in the 60” cyclotron, and such particles in the Berkeley bevatron would be accelerated to more than 36 BeV Since in the cosmic radiation such heavy particles play an important role, they will surely be produced in the bevatron some day, contributing to further progress in our understanding of Nature.

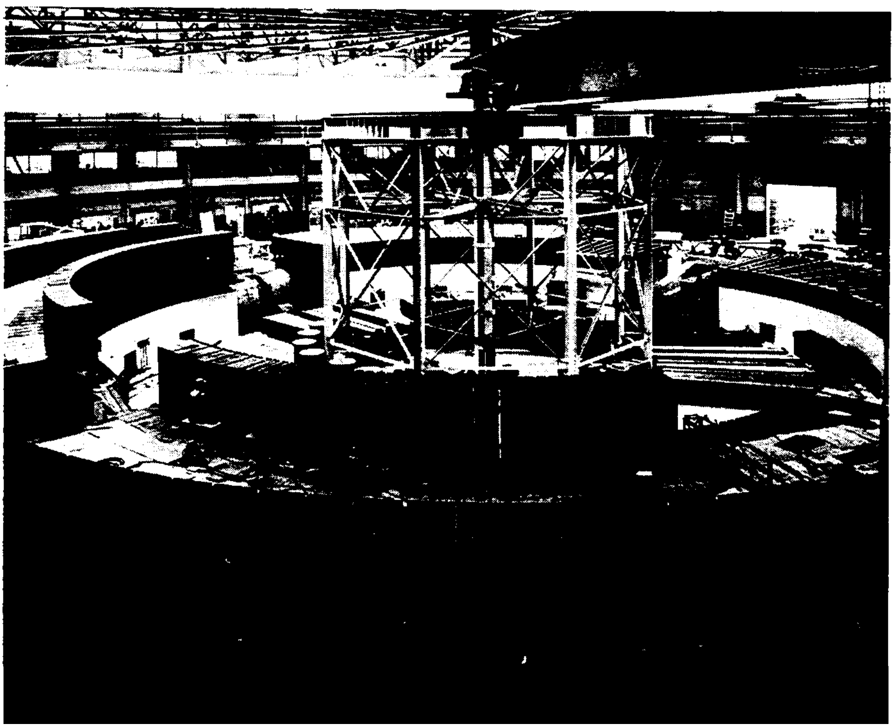

Fig. 12. General view of <<race track>> magnet in process of assembly for 6.3 BeV proton synchrotron or <<bevatron>>.

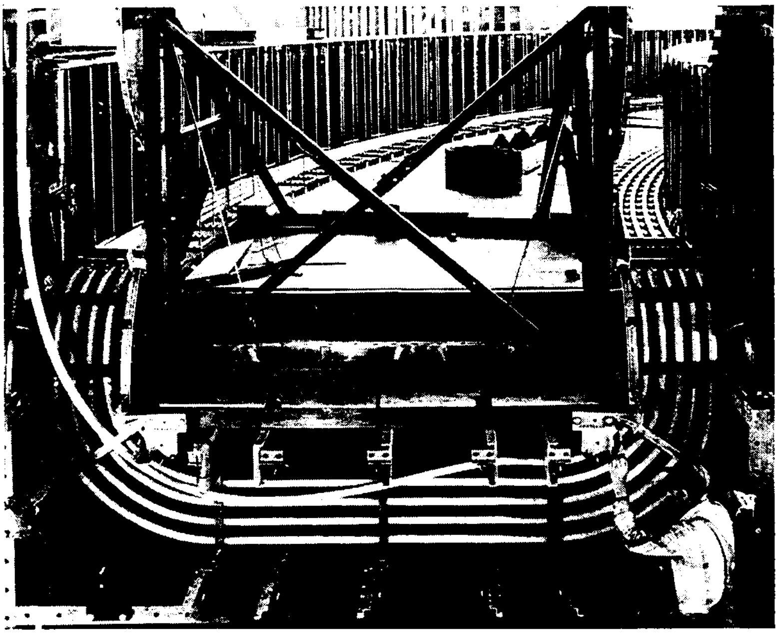

Fig. 13. Showing coil winding of bevatron magnet.

Fig. 14. The size of the bevatron magnet is here indicated .(*Left to right*: E. O. Lawrence, W. M. Brobeck, H. A. Fidler, and D. Cooksey).

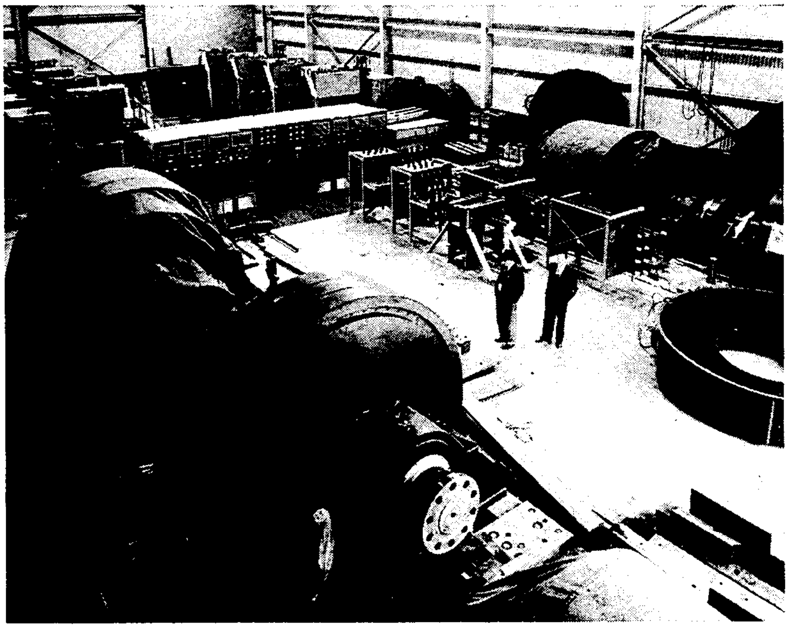

Fig. 15. Bevatron motor generator equipment.

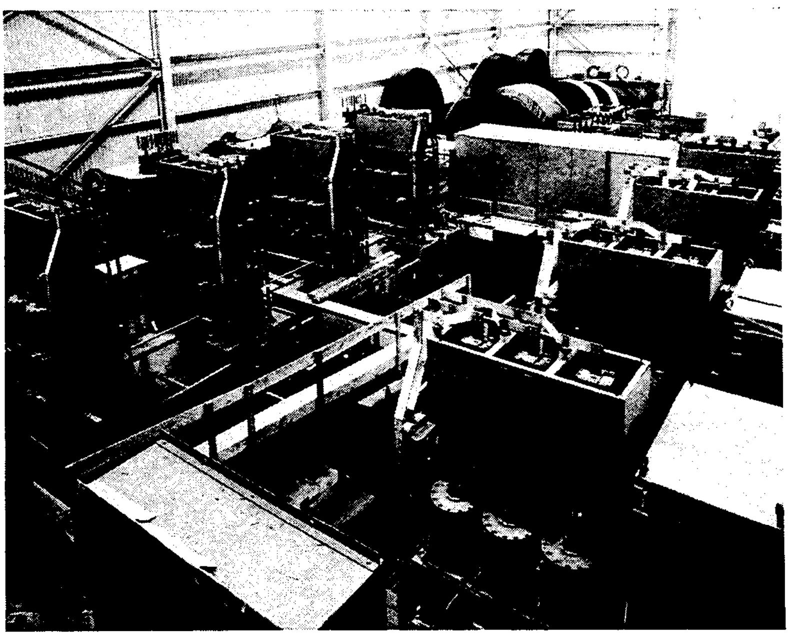

Fig. 16. Ignitrons and associated switchgear for bevatron motor generator.

Biography

Ernest Orlando Lawrence was born on 8th August, 1901, at Canton, South Dakota (United States). His parents, Carl Gustavus and Gunda (née Jacobson) Lawrence, were the children of Norwegian immigrants, his father being a Superintendant of Schools. His early education was at Canton High School, then St. Olaf College. In 1919 he went to the University of South Dakota, receiving his B.A. in Chemistry in 1922. The following year he received his M.A. from the University of Minnesota. He spent a year at Chicago University doing physics and was awarded his PbD. from Yale University in 1925. He continued at Yale for a further three years, the first two as a National Research Fellow and the third as Assistant Professor of Physics. In 1928 he was appointed Associate Professor of Physics at the University of California, Berkeley, and two years later he became Professor, being the youngest professor at Berkeley. In 1936 he became Director of the University's Radiation Laboratory as well, remaining in these posts until his death.

During World War II he made vital contributions to the development of the atomic bomb, holding several official appointments in the project. After the war he played a part in the attempt to obtain international agreement on the suspension of atomic-bomb testing, being a member of the U.S. delegation at the 1958 Geneva Conference on this subject.

Lawrence's research centred on nuclear physics. His early work was on ionization phenomena and the measurement of ionization potentials of metal vapours. In 1929 he invented the cyclotron, a device for accelerating nuclear particles to very high velocities without the use of high voltages. The swiftly moving particles were used to bombard atoms of various elements, disintegrating the atoms to form, in some cases, completely new elements. Hundreds of radioactive isotopes of the known elements were also discovered. His brother, Dr. John Lawrence, who became Director of the University's Medical Physics Laboratory, collaborated with him in studying medical and biological applications of the cyclotron and himself became a consultant to the Institute of Cancer Research at Columbia.

Larger and more powerful versions of the cyclotron were built by Lawrence. In 1941 the instrument was used to generate artificially the cosmic particles called mesons, and later the studies were extended to antiparticles.

Lawrence was a most prolific writer: during 1924-1940 his name appeared on 56 papers (an average of 3½ papers a year), showing his exceptional breadth of interest. He was also the inventor of a method for obtaining time intervals as small as three billionths of a second, to study the discharge phenomena of an electric spark. In addition he devised a very precise method for measuring the e/m ratio of the electron, one of the fundamental constants of Nature. Most of his work was published in *The Physical Review* and the *Proceedings of the National Academy of Sciences.*

Among his many awards may be mentioned the Elliott Cresson Medal of the Franklin Institute, the Comstock Prize of the National Academy of Sciences, the Hughes Medal of the Royal Society, the Duddell Medal of the Royal Physical Society, the Faraday Medal, and the Enrico Fermi Award. He was decorated with the Medal for Merit and was an Officer of the Legion of Honour. He held honorary doctorates of thirteen American and one British University (Glasgow). He was a member or fellow of many American and foreign learned societies.

Lawrence married Mary Kimberly Blumer, daughter of the Emeritus Dean at Yale Medical School, in May 1932. They had six children. His recreations were boating, tennis, ice-skating, and music. He died on 27th August, 1958, at Palo Alto, California.

Physics 1940

Prize not awarded.

Physics 1941

Prize not awarded.

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