Supplement to NATURE

No. 3084 DECEMBER 8, 1928

The Quantum Theory.[1]

By Prof. H. S. ALLEN, University of St. Andrews.

IN a lecture on the quantum theory it might be thought fitting to commence with a clear explanation of the purpose, nature, and scope of the subject; but an attempt to answer briefly the question, 'What is the quantum theory?' would prove as baffling as Osborne Reynolds found the answer to the question, What is thermodynamics? He confessed that he felt tempted to reply:

> "It is a very difficult subject, nearly, if not quite, unfit for a lecture. The reasoning involved is such as can only be expressed in mathematical language. But this alone should not preclude the discussion of the leading features in popular language. The physical theories of astronomy, light, and sound, involve even more complex reasoning, and yet these have been rendered popular, to the very great improvement of the theories."

The discussion of the quantum theory, however, presents a further and perhaps a greater difficulty. When Osborne Reynolds lectured on the general theory of thermodynamics in 1883, the foundations of the subject had been well and truly laid by the labours of those nineteenth-century leaders of physical science, Carnot, Joule, Clausius, Thomson, and Helmholtz. But even yet we are not quite satisfied as to the foundations of the quantum theory. Builder's rubble is still scattered over the ground, and the building itself is still in process of erection. Although the first stone was laid by Dr. Max Planck, professor of theoretical physics in the University of Berlin, on Dec. 14, 1900, the scaffolding has not yet been removed, and it is difficult, if not impossible, to get a bird's-eye view of the structure.

The quantum theory, though it has not attracted so much popular attention as the theory of relativity, has created problems of equal if not greater philosophical and scientific importance. The most acute question in physics at the present time is the problem of the nature of light. Is light corpuscular or undulatory in structure? In 1905, Einstein first suggested the hypothesis of light quanta. It is as though in digging the ground for the new theory he had unearthed the foundations of Newton's corpuscular theory and employed them in the construction of a new building; and all the time across the way was the magnificent structure of the undulatory theory of light erected by the labours of Huyghens, Young, and Fresnel, and enriched by the genius of Clerk Maxwell.

Up to the present no one has bridged the gulf between these two buildings. Many attempts have been made to build a bridge, but the keystone of the arch has not been fitted. Physicists are obliged to live sometimes in one building, sometimes in the other. We use either hypothesis according to the nature of the problem that we have under consideration, or, as Sir William Bragg expressed it in his presidential address to the British Association at Glasgow:

> "On Mondays, Wednesdays, and Fridays we adopt the one hypothesis, on Tuesdays, Thursdays, and Saturdays the other. We know that we cannot be seeing clearly and fully in either case, but are perfectly content to work and wait for the complete understanding."

LIGHT QUANTA.

According to Einstein's hypothesis, the energy of radiation, instead of spreading out in all directions from the source as the undulatory theory of light would lead us to expect, is concentrated in certain bundles or units of energy so that propagation takes place in a manner closely resembling that met with in the corpuscular theory. There are certain phenomena which would lead us to the conclusion that the energy of a quantum is not only definite in amount, but is also concentrated in space, being always confined to a very small volume.

One way of picturing this concentration is to suppose with J. J. Thomson that the energy travels along discrete lines of electric force, so that the front of a wave of light would suggest the appearance

---

[1] From a lecture on "Some Philosophical Aspects of the Quantum Theory," delivered to the St. Andrews University Philosophical Society, Oct. 29, 1928.

of a number of bright spots on a dark ground. There are serious objections to this particular picture of the propagation of light, but it does seem necessary to suppose that each unit of energy can only be absorbed or emitted as a whole. This hypothesis is consistent with the experimental facts observed when electrons are separated from atoms by the action of light or X-rays—the so-called photoelectric effect. When the light quantum gives up its energy, it may be assumed that the energy is transferred to a single electron, so that the latter leaves the body with a corresponding amount of kinetic energy, allowance being made for the work the electron has to do in leaving the body. Einstein's hypothesis, however, seems inconsistent with the phenomena of interference and diffraction, which require some form of wave theory for their explanation.

THE RADIATION PROBLEM.

Towards the close of the last century, an unexpected difficulty confronted physicists with regard to the spectrum of the radiation inside a hollow body maintained at a constant high temperature. The light issuing from a small opening in the wall of the enclosure was examined by using a prism, and the energy in different parts of the spectrum was measured. The results of such measurements could not be forced into agreement with classical theory. The latter predicts a definite relation between the energy emitted for a certain wave-length (or, more strictly, for a small range of wave-lengths) in the spectrum and the wave-length of that particular region. The results of the experiments do not conform with this relation.

If we adopt the principles of classical mechanics in dealing with radiation, as was done in an important investigation by the late Lord Rayleigh, there seems no escape from the conclusion that the way in which the energy is distributed amongst the wave-lengths in a normal spectrum must follow a definite mathematical law, now known as Rayleigh's law. According to this law, the energy should be the greater the smaller the wave-length of the radiation considered ; in fact, for very short wave-lengths the energy should tend to assume an infinitely great value. This is directly contrary to experience. Careful experiments have shown that the energy of radiation is a maximum for a particular wave-length, and when the wave-length is less than the particular value, the energy is smaller than the maximum, becoming extremely small for the very short waves.

It was to meet this difficulty that Planck assumed the existence of vibrators of frequency ν, which could only possess energies of amount $h\nu$, $2h\nu$, $3h\nu$, . . . and no other. Thus he introduced the hypothesis of energy quanta. According to this hypothesis, radiant energy of any assigned frequency ν can be emitted and absorbed only as an integral multiple of *an element of energy*, $h\nu$, where h is a constant of Nature, now known as Planck's constant.

We may feel some hesitation in speaking of an 'atom' of energy, since the energy depends upon the frequency and the true constant is the factor h ; but we may say that the radiation behaves as though it were done up in parcels or bundles, each parcel possessing an amount of energy, $nh\nu$ (n integral), proportional to the frequency of the radiation considered.

Another way of regarding the matter is to pay attention to the factor h itself. This is a quantity having the 'dimensions' of *action*, that is, energy multiplied by time. It is probably significant that, in the theory of relativity, action becomes more important than energy, and action rather than energy is conserved.

There is yet another way of interpreting Planck's constant, and that is to regard it as determining a natural unit of angular momentum (J. W. Nicholson), the physical 'dimensions' of angular momentum being the same as those of action. The angular momentum may be expressed in terms of a unit $h/2\pi$.

INTEGRAL RELATIONS IN SCIENCE.

It is almost impossible to exaggerate the importance which attaches to the occurrences of integers in physical science. Integral relations between the *masses* of gases entering into chemical combination with one another confirmed Dalton's theory of the atomic constitution of matter (1803), a theory first suggested to his mind by a study of the physical properties of gases. The chemical elements are composed of extremely minute particles (atoms) which are indestructible and indivisible *in chemical changes*. The law of Gay-Lussac (1805), that there is a simple relation between the *volumes* of the interacting gases, led Avogadro to his celebrated hypothesis, which is based on a clear distinction between the molecule and the atom. The molecules of elementary gases are not necessarily the atoms themselves, but may consist of clusters of atoms moving about as though they were single particles.

The imagination is almost overwhelmed when we attempt to visualise the enormous numbers of atoms or molecules which are present in even a small amount of material substance. But we recall the story in the Arabian Nights Entertainment—" And then another locust came and carried off another grain of corn "—and we may then appreciate better the almost illimitable number of natural objects and processes.

The atomicity of electricity foreshadowed in Faraday's work on electrolysis was brilliantly established by the measurements of J. J. Thomson, who determined the charge of the electron, the fundamental unit of negative electricity.

Integral relations obtained by Millikan in his experiments on the motion of small electrified particles have furnished indisputable evidence of the atomic nature of electricity. Speaking of the beauty and precision of these results, he says: " No more exact or more consistent multiple relationship is found in the data which chemists have amassed on the combining powers of the elements, and on which the atomic theory of matter rests, than is found in the foregoing numbers." An electric charge wherever it is found consists of an exact number of specks of electricity (electrons) all exactly alike. Thus is confirmed the view suggested by Faraday that " the atoms of bodies which are equivalent to each other in their ordinary chemical action have equal quantities of electricity naturally associated with them."

The atomic number of an element represents not only the number of extra-nuclear or planetary electrons, but also the resultant positive charge of the nucleus itself.

We recall the fact that in 1815 Prout emphasised the nearly integral values of the atomic weights of a number of elements, and suggested that all the elements were built up of one common material, hydrogen. The atom of any other element he supposed to be an extremely stable combination of hydrogen atoms. This suggestion led to a close examination of atomic weights, but after a series of accurate experiments, Stas still obtained fractional values for certain elements, and was led to characterise Prout's hypothesis as " an illusion, a mere speculation definitely contradicted by experience." Within recent years the position has been completely changed through the discovery of the existence of isotopes, that is, substances differing in atomic weight, but having identical chemical properties. This discovery makes it possible to explain fractional atomic weights as arising from the existence of two or more isotopes, and thus justifies a revival of Prout's hypothesis.

Direct evidence in favour of the idea that an atom of, say, nitrogen is composed of hydrogen atoms is afforded by the experiments of Rutherford on the disintegration of the nitrogen nucleus by bombardment with a swiftly moving alpha particle. Again, the marvellous experiments of Aston, using his mass-spectrograph, have shown that a whole number may be applied to the relative *masses* of the majority of the elements when oxygen ($O=16$) is selected as a standard. The masses of the atoms of almost all the elements measured may then be expressed as whole numbers to an accuracy of about one part in a thousand. This clearly suggests a return to Prout's hypothesis that the atoms of the elements are different aggregations of atoms of hydrogen. The modern statement of the hypothesis would be: " the atoms of the elements are aggregations of electrons and protons "—the proton being the positively charged part remaining when an electron is detached from a neutral hydrogen atom.

THE RUTHERFORD-BOHR ATOM.

The dynamic model of the atom suggested by Rutherford (1911) and developed by Bohr (1913) may be termed an astronomical atom, as the motion of the electrons round the massive nucleus may be compared to the motion of the planets round the sun. The similarity arises from the fact that the force of electrical attraction between electron and nucleus obeys the same law as the Newtonian law of gravitation and is inversely proportional to the square of the distance between the bodies concerned.

Newton was the first to prove that the law of force, now familiar as the *inverse square law,* gives an elliptic orbit as required by Kepler's first law.

Kepler's second law of the constancy in the rate of description of radial areas means that the moment of momentum, or the angular momentum, of the particle about the origin is constant throughout the motion.

Let us consider an atom in which electrons are revolving about a nucleus and are subject to the force of electric attraction towards the nucleus, and for the time being let us neglect the mutual influence of the electrons upon one another. Then each electron must have a constant moment of momentum characteristic of its particular orbit.

In Bohr's first statement of his theory he dealt with the problem of a single electron revolving round a massive nucleus, as in the neutral hydrogen atom. He employed the quantum condition of Nicholson, and in this way fixed the angular momentum of the electron, putting it equal to a multiple of $h/2\pi$. The electron can then revolve only in certain selected or 'permitted' orbits which are allowed by the quantum relation.

The simplest illustration of the application of the quantum condition is afforded by the circular orbits of the hydrogen atom. The innermost orbit corresponds to the normal state of the atom. But it is possible, according to Bohr's original presentation of his theory, for the electron to move in other stable orbits, and it is found that the radii of successive orbits increase as the squares of whole numbers, that is to say, as 1, 4, 9, 16, 25 . . ., and so on. The energy associated with a particular orbit varies inversely as the diameter of the orbit, and consequently inversely as the square of the corresponding 'quantum number.' The series of states thus suggested may be regarded as a set of energy levels. Bohr supposes that it is possible for an electron to 'jump' in some way not described from one such level to another and in so doing to emit or absorb radiation. When the electron falls from an outer orbit to the innermost orbit, a line of the Lyman series is emitted. If, however, the final orbit is the second from the centre, a line of the Balmer series is emitted. The Paschen series is produced when the electron passes into the third orbit.

In the later developments of the theory by Wilson and Sommerfeld, elliptic orbits were considered and it was found possible to give an explanation of the fine structure of the lines of hydrogen and ionised helium. In the discussion of the 'stationary states' of the dynamical system, certain quantum restrictions have to be imposed so as to determine the 'permitted' orbits. These quantum conditions may be expressed by saying that the integrals of action during a complete period must be a multiple of the constant h.

THE QUANTUM POSTULATES.

The older quantum theory was based by Bohr upon certain fundamental postulates which represent a definite departure from the results obtained by considering a system of particles satisfying the laws of classical dynamics. The first postulate affirms the existence of 'stationary' states in which, contrary to the principles of Maxwell's electromagnetic theory, no radiation is either emitted or absorbed. The second postulate is contained in Bohr's frequency relation :

$$\pm h\nu = E' - E'',$$

which affirms that in the transition between two stationary states one quantum of monochromatic radiation is either emitted or absorbed. Here again appears a striking departure from classical theory, and even a departure from accepted ideas as to causality. For it looks as if the kind of radiation emitted depends not only on the state of affairs before the emission takes place, but also on the state after the emission has occurred.

Bohr's suggestion of 1913 that an electron attached to an atom could emit light only by making a discontinuous jump from one possible orbit to another, quite distinct, orbit has provoked much speculation. To explain this puzzling behaviour it has been suggested that the electron may have some freedom of choice, so that it is impossible to predict to which possible orbit the transition will take place.

In my opinion such a revolutionary hypothesis is not demanded either by the facts or by the model. It is better to regard the atomic model as imperfect in its original form, and to suppose with E. T. Whittaker that sufficient attention has not been paid to the happening at the place to which the jump occurs. Whittaker pictures two coincident electrons, one positive and one negative, at this place ; the opposite charges annul one another and are without effect in the initial state of the system. Emission of radiation is brought about by some external agency which stimulates the discharge of a condenser composed of the excited outer electron and one of these two charges. The other charge is left surviving alone at the end of the process, which is accordingly equivalent to Bohr's notion of a translation of the outer electron to an inner orbit.

In a very interesting essay on the future of physics, L. L. Whyte has laid stress on the assumption of *reversibility* implicit in Newton's laws, which, he claims, is valid neither for atom nor for organism. If it were once admitted that any elementary process were irreversible, it would be necessary to give up the whole system of Newtonian conceptions, which are unsuitable for the treatment of irreversible effects. In his suggestive volume "Archimedes" the issue is formulated thus :

> "Is there a real temporal process in Nature ? Is the passage of irreversible time a necessary element in any view of the structure of Nature ? Or, alternatively, is the subjective experience of time a mere illusion in the mind which cannot be

> given objective expression? These are not metaphysical questions that can still be neglected by science with impunity. . . . Moreover, the above questions may be put into precise scientific form by asking if the causal relations which are studied by science are symmetrical and reversible so that we cannot obtain from them any criterion by which to distinguish past and future. If, on the other hand, they are asymmetrical and irreversible, the laws of Nature lead us on necessarily from what went before to what comes afterwards."

If Born is correct in asserting that all quantum processes are irreversible, the philosophical implications are of the utmost importance.

In classical dynamics a knowledge of the position and velocity of all the particles composing a system determines the future motion of the system, and that completely. Thus, when the state of the system is known at a particular instant, it is possible (theoretically) to foretell the state of that system at any later instant.

Laplace visualised this possibility in a famous passage:

> " A mind to which were given for a single instant all the forces of Nature, and the mutual positions of all its masses, if it were otherwise powerful enough to subject these problems to analysis, could grasp, with a single formula, the motions of the largest masses as well as of the smallest atoms; nothing would be uncertain for it; the future and the past would lie revealed before its eyes" ("Essai philosophique sur les probabilités," 1840).

This expresses the meaning of the principle of causality on the basis of the older dynamical theory. The idea of knowing exactly the state of a system at some given moment is never realised in practice, and consequently the introduction of considerations of probability is justified and statistical methods were frequently employed.[2]

MATRIX MECHANICS.

Heisenberg put forward the demand that only such quantities as are observable should be represented in the mathematical formulation of atomic theory. The selected orbits of the older theory cannot be directly observed and cannot, even ideally, be subjected to measurement. On the other hand, the frequencies and intensities of the light emitted, scattered, or absorbed by an atom can be both observed and measured. This led to the development of the matrix mechanics, every term in a matrix corresponding to something which is, at least ideally, observable. The dynamics of matrices may be regarded as a generalisation of classical dynamics, the latter being the limit of the former. Instead of the quantum conditions of the earlier theory, the quantum constant h is now introduced in an equation expressing the fact that the rule of multiplication in the new mechanics is non-commutative. In fact, if p and q are conjugate canonical variables, we have $pq - qp = h/(2\pi i)$. This is known as Heisenberg's uncertainty relation.[3]

There is a further point of difference between classical mechanics and the more recent quantum theory, which has been emphasised by Heisenberg. In the older theory the position of a particle can be definitely fixed at a specified moment by means of its co-ordinates. As the time varies it is supposed to be possible to follow the track of the particle through space, or to determine its 'world-line' in the four-dimensional world. In the new quantum theory both the position and the path of a particle become vague. It is argued that the position or trajectory of an electron can only be determined by illuminating the electron by a beam of light, and this illumination itself will interact with the electron, rendering the exact measurement of position or path impossible. There is an element of uncertainty in the proposed determination, the amount being specified by Heisenberg's 'uncertainty relation.'

This relation involves the positional co-ordinate q, and also the momentum (impulse co-ordinate) p, and may be interpreted by saying that when we try to determine exactly where the electron is—and to do this we have to use a beam of light—it behaves in such a way that we are unable to measure simultaneously its exact velocity.

WAVE MECHANICS.

Louis de Broglie threw fresh light on the difficulties which had become so serious in quantum theory, in a series of papers in which a material particle was regarded as closely associated with a group of waves having velocity and wave-length governed by the speed and mass of the particle. Every such particle when at rest is the centre of a pulsation extending throughout space. This means that the ' particle ' is to be treated as a singularity of a pulsation which at any given time is in the same phase through space. We may consider these pulsations throughout boundless space as in some respects analogous to standing waves along

---

[2] See an article by H. F. Biggs (NATURE, Vol. 121, p. 503; 1928).

[3] The occurrence of the imaginary quantity $i = \sqrt{-1}$ in this equation is remarkable, and may be significant. Written in the form $ipq - iqp = h/2\pi$, the relation suggests that the fundamental phenomenon in microscopic processes is gyroscopic in nature.

a finite string or in an organ pipe. Another imperfect analogy may be found in the vibrations of a bell or Chladni's plate.

When the 'particle' is moving with reference to the observer with uniform velocity, the pulsations will no longer be simultaneous but will be represented by travelling waves.

> "The 'region occupied by the particle' is the region where a set of these waves, varying continuously in direction and in frequency over a small range, reinforce each other to form a *wave-group* travelling with what we call 'the velocity of the particle.'"

The velocity of a particle thus appears as a *group velocity*. The consequences of this theory, as developed by Schrödinger and others, have been tested by their application to problems of spectroscopy and by more direct evidence derived from experiments on the reflection of electrons from crystals (Davisson) and on the patterns formed by the passage of cathode rays through very thin films (G. P. Thomson). These patterns are similar to those obtained with X-rays in the 'powder' method and agree in dimensions with the predictions of wave mechanics.

An interesting, though somewhat problematical, application of the ideas of de Broglie accounts for the integral relations in Bohr's circular orbits. By imagining a ray of the waves to travel round the circular orbit, and introducing the condition that the circumference contains a whole number of wave-lengths, the angular momentum of the electron is restricted to the values previously assigned. In this connexion it is interesting to recall the views of Sutherland (1901) with regard to the origin of lines in spectral series. He came to the conclusion that the series must arise from kinematical considerations, and explained them by considering the nodal subdivisions of a circle. A similar idea was put forward in the Physical Society discussion on the ring electron in 1918.

Views analogous to those of de Broglie have been published by J. J. Thomson in a lecture entitled "Beyond the Electron" (1928). The electron "has a dual structure, one part of this structure, that where the energy is located, being built up of a number of lines of electric force, while the other part is a train of waves in resonance with the electron and which determine the path along which it travels." This view is very similar to the view of the structure of light suggested by J. J. Thomson in 1924. "This duality is a necessary consequence of the transmission of energy through the ether by waves: for this involves two things, the transmission of energy and the propagation of the waves." The transmission of energy takes place with the 'group' velocity, the transmission of waves with the 'wave' velocity. "If we concentrate on the waves we have an undulatory theory; if on the energy a corpuscular one."

The most promising attempt yet made to *explain* quantum phenomena and the existence of quantum numbers is undoubtedly that of Schrödinger in his undulatory mechanics. We have here the nearest approach to classical principles in the formulation of the wave equation and in the suggested interpretation of the wave function ψ.

As pointed out long ago by Hamilton, there is a close analogy between mechanics and optics; in fact, his theory of mechanics grew out of his "Optics of Non-homogeneous Media." Classical mechanics is analogous to geometrical optics. The motion of a material system may be studied by considering the path of a mass-point in configuration space, that is, the space of the variables which are *positional* co-ordinates. To the path of this representative point in configuration space there corresponds the path of a ray of light in geometrical optics. But we know that geometrical optics fails to account for the facts and must be replaced by undulatory optics as soon as the obstacles or apertures are no longer great compared with the wave-length. We also know that in the atomic domain classical mechanics fails, the failure becoming evident when the curvature of the path becomes very great. This suggests that we really require an undulatory mechanics which may be regarded as the Hamiltonian analogy of undulatory optics. Wave mechanics bears to ordinary mechanics the same relation as undulatory optics bears to geometrical optics.

It has been said in picturesque language that according to Schrödinger: "Nature is not made up of electrons but of waves. The atom must be considered as a system of electric waves spread over its whole volume. 'Electrons' are merely an inaccurate way of describing some of the properties of these waves" (L. L. Whyte).

It is important to remember, however, that Schrödinger's waves are not waves in ordinary space, but waves in 'configuration space,' which has as many dimensions as there are degrees of freedom of the system. Disregarding rotation, this would be $3N$ for a system composed of N particles. It is only in dealing with the one-electron problem that we are able to use space of three dimensions.

In macro-mechanical problems classical dynamics may be employed. In micro-mechanical motions the equations of the old dynamics are no longer valid; they must be replaced by a *wave-equation* in configuration space. This equation contains a parameter E, which corresponds to the mechanical energy in macroscopic problems. It is only for certain special values of E, the *proper values*, that the wave equation possesses solutions which (together with their derivatives) are one-valued, finite and continuous throughout configuration space. These proper values include the 'energy levels' of the older quantum theory, the quantum numbers arising in a straightforward way out of the wave-equation. Thus in Schrödinger's undulatory mechanics "quantum numbers are accounted for in a perfectly natural way, practically on classical principles," or, as de Broglie has expressed it: "The appearance of integers in the dynamical formulæ ceases to be mysterious, and becomes as natural as their occurrence in the theory of vibrating strings or of wireless antennæ."

The integral relations thus obtained represent one of the triumphs of the new theory, and it is found that when the energy levels thus determined are not in exact agreement with those previously deduced, the deviations are all actually in favour of the new mechanics. It is especially noteworthy that the results of Heisenberg's quantum mechanics agree with those of the undulatory mechanics, where there is a difference from the old quantum theory. As Schrödinger points out, this is the more remarkable, as the whole mathematical apparatus seems fundamentally different in the two methods.

Dirac has developed an even more general method of treatment, which may be called a quantum algebra. For the representation of atomic quantities he introduces quantum variables or quantum numbers (q-numbers). These are subject to the ordinary arithmetical laws, with the exception that they do not obey the commutative law of multiplication. By employing certain additional hypotheses, Dirac is able to express the mechanical laws in Hamiltonian form. Born and Wiener have suggested that quantum magnitudes may be considered as functional operators, an idea that would account for the failure of the commutative law, since the successive application of two *operations* may depend on the order in which they are carried out. A further point of interest to the mathematician is the analogy between the theory of matrices and that of integral equations (Lanczos).

THE NEW OUTLOOK.

We may summarise the chief results of this recent work as follows. In classical theory we have been accustomed to deal with point events and with the movement of mass particles. Now the picture becomes blurred, or at least less sharp and clear. No longer are we to consider a mathematical point in three-dimensional space, but instead a small *region* in the space-time world. The concept of a massive particle of infinitesimal size is to be replaced by the idea of a focus of waves. For the path of a particle, which corresponds to a ray in geometrical optics, must be substituted the track of a group of waves as in physical optics. In spite of these differences in outlook, we are assured by Bohr that we have to deal not with *contradictory* but with *complementary* pictures.

The older or classical quantum theory is based on stationary states and quantum jumps. Schrödinger endeavoured to retain so far as possible classical conceptions, in which there are no discontinuities. Thus there has arisen a difference in outlook between Schrödinger and other workers in this field. For example, Born and Jordan hold that Schrödinger's relations have to be interpreted in a statistical sense. According to Schrödinger, quantum mechanical laws can be expressed by quite ordinary differential equations; according to Born, the reason why it is possible "to represent anything in the discontinuous confusion of quantised atomic processes by differential equations, is that the function which is to satisfy the differential equation is a probability."

Jordan (NATURE, vol. 119, p. 568; 1927) sums up this position in the following words: "Classical physics described the world in terms of quantities continuously propagated in space and time. The quantum theory describes the world in terms of an abstract, many-dimensional configuration space, and the number of dimensions is proportional to the total number of particles in the world. In this abstract space we have again the propagation of continuous quantities; but these no longer tell us directly about the single atomic phenomena, but rather about the probabilities of the quantum processes. Determinism—not as a metaphysical distinction from chance, but in the physical sense explained above—has the same formal validity in both theories."

Jordan concludes his review of the philosophical problem by saying: "Probably we shall find that an incomplete determinism, a certain element of pure chance, is intrinsic in these elementary physical laws."

Earlier in this address, emphasis was laid on the requirement that light should possess a certain structure so as to afford points of concentration of radiant energy—a requirement which is difficult to reconcile with the undulatory theory. On the other hand, it now appears necessary to introduce into the classical picture of material particles some of the characteristics of wave motion. Is it possible to combine these two problems into one and effect a synthesis between a corpuscular and a wave theory both for radiation and for matter? This question has been discussed by de Broglie, who suggests that the exact description of the phenomena can only be given through the consideration of waves *which admit of singularities*. In his view the material particle is an essential reality, and its motion is completely determined as that of a singularity in the amplitude of a wave which is propagated.

"It would in this way be possible to retain the atomic structure of matter and of radiation, as well as the determinism of individual phenomena, while at the same time attributing to the continuous solutions the statistical meaning which Born and implicitly Schrödinger have recognised in them."

Bohr has discussed the significance of recent developments in the quantum theory in an important, though difficult, paper published last April (NATURE, Vol. 121, p. 580). The quantum postulate "attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories, and symbolised by Planck's quantum of action." Bohr believes that the causal space-time description of phenomena to which we are accustomed in dealing with macroscopic phenomena may fail us when we have to do with atomic (microscopic) phenomena. This failure arises from the small value of the quantum of action as compared with the actions involved in ordinary sense perceptions. The situation is illustrated by considering the question of the measurement of the co-ordinates of a particle, taking into account Heisenberg's relation between them. This relation implies a certain maximum precision with which the space-time coordinates and momentum-energy components of a particle can be measured simultaneously.

At the outset we compared the corpuscular theory and the wave theory to two separate buildings. Perhaps Bohr's latest work may be regarded as an attempt to dig an underground passage between the two, but the tunnel is dark and gloomy, and the atmosphere scarcely fit for human respiration. We might wish to find another solution like that proposed by the philosopher Alice in "Through the Looking-Glass":

> "She went on and on, a long way, but wherever the road divided there were sure to be two finger-posts pointing the same way, one marked 'TO TWEEDLEDUM'S HOUSE,' and the other, 'TO THE HOUSE OF TWEEDLEDEE.' 'I do believe,' said Alice at last, 'that they live in the same house! I wonder I never thought of that before.'"

But Alice never found the house, and when she met the two little men, conversation proved difficult.

> "I know what you're thinking about," said Tweedledum; "but it isn't so, nohow."
>
> "Contrariwise," continued Tweedledee, "if it was so, it might be; and if it were so, it would be; but as it isn't, it ain't. That's logic."

We had better abandon the simile of the house and try another analogy. We may liken the 'complementary' theory of Bohr to a see-saw on which Tom Particle and Mary Wave are so evenly balanced that a touch will send one end of the plank up or down. If we attempt to fix one end to mother earth, the other is suspended in mid-air. But fixity is not one of the essentials of a see-saw, and however much we may desire a firm foundation for a scientific theory, it is at least possible that fixity is not attainable by finite human intelligence. Bohr concludes his article by pointing out that in the scientific situation there is a deep-going analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object.

In philosophy, as in science, it is generally admitted that there has been a movement away from the mechanical view of Nature which dominated the nineteenth century. The new movement, as expressed, for example, in the writings of A. N. Whitehead, is towards "the recognition of purposiveness and creativeness in Nature." It is difficult to understand all the implications of Whitehead's work, but in his view, as in that of Bergson, the basic idea of *process* must be employed in building up a scientific philosophy. In the organic theory of Nature we have to consider, not a bit of material as in the materialistic theory, but a complete *organism.* In the physical field the primary organisms appear to be vibratory entities, and a proton or electron may perhaps be regarded as a vibrating pattern—a view not very different from that of Schrödinger. "The path in space of such a vibratory entity—where the entity is constituted by the vibrations—must be represented by a series of detached positions in space." Thus it will be seen that Whitehead's views are in harmony with the ideas of the quantum theory, although it is as yet too early to regard that theory as entirely comprehensible.

What, then, is the conclusion of the whole matter? Biologists, chemists, engineers, and also philosophers, are looking to the physicist to give a clear pronouncement as to the nature of fundamental physical processes. At the present moment no clear unambiguous reply is possible. We are still at the stage in which exploration of scientific facts is needed, and, on the other hand, candid examination of the basic ideas in philosophy is required. One lesson at least is emphasised by the recent history of scientific thought, and that is the necessity for caution and modesty in our approach to these fundamental conceptions. We often find discarded theories re-born, and we may learn even from the mistakes of the leaders in science.

Truth, in the realm of physical science, is no longer enshrined in a pellucid crystal sphere. Rather it is to be found in a quivering, pulsating orb of fire. The rainbow colours change as we gaze upon it, and from time to time dark clouds obscure our view. In the search for truth the mental philosopher and the natural philosopher must join forces; and the quest is worth while: "For wisdom is more mobile than any motion. Yea, she pervadeth and penetrateth all things by reason of her pureness. For she is an effulgence from everlasting light."

Printed in Great Britain by R. & R. CLARK, LIMITED, *Edinburgh.*