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The Quantum of Action and the Description of Nature

(1929)

In the history of science there are few events which, in the brief span of a generation, have had such extraordinary consequences as Planck's discovery of the elementary quantum of action. Not only does this discovery, to an ever increasing degree, form the background for the ordering of our experience concerning atomic phenomena, the knowledge of which has been so amazingly extended in the last thirty years, but, at the same time, it has brought about a complete revision of the foundations underlying our description of natural phenomena. We are dealing here with an unbroken development of points of view and conceptual aids which, beginning with the fundamental works of Planck on black body radiation, has reached a temporary climax, in recent years, in the formulation of a symbolic quantum mechanics. This theory may be regarded as a natural generalization of the classical mechanics with which in beauty and self-consistency it may well be compared.

This goal has not been attained, still, without a renunciation of the causal space-time mode of description that characterizes the classical physical theories which have experienced such a profound clarification through the theory of relativity. In this respect, the quantum theory may be said to be a disappointment, for the atomic theory arose just from the attempt to ac-

complish such a description also in the case of phenomena which, in our immediate sense impressions, do not appear as motions of material bodies. From the very beginning, however, one was not unprepared in this domain to come upon a failure of the forms of perception adapted to our ordinary sense impressions. We know now, it is true, that the often expressed scepticism with regard to the reality of atoms was exaggerated; for, indeed, the wonderful development of the art of experimentation has enabled us to study the effects of individual atoms. Nevertheless, the very recognition of the limited divisibility of physical processes, symbolized by the quantum of action, has justified the old doubt as to the range of our ordinary forms of perception when applied to atomic phenomena. Since, in the observation of these phenomena, we cannot neglect the interaction between the object and the instrument of observation, the question of the possibilities of observation again comes to the foreground. Thus, we meet here, in a new light, the problem of the objectivity of phenomena which has always attracted so much attention in philosophical discussion.

This being the state of affairs, it is not surprising that, in all rational applications of the quantum theory, we have been concerned with essentially statistical problems. Indeed, in the original researches of Planck, it was, above all, the necessity for modifying the classical statistical mechanics which gave rise to the introduction of the quantum of action. This feature, which is characteristic of the quantum theory, is strikingly expressed in the recently renewed discussion on the nature of light and of the elementary particles of matter. Although these questions had apparently found their final solution within the compass of the classical theories, we know now that for material particles as well as for light different conceptual pictures are necessary to account completely for the phenomena and to furnish a unique formulation of the statistical laws which govern the data of observation. The more clearly it appears that a uniform formulation of the quantum theory in classical terms is impossible, the more we admire Planck's happy intuition in coining the term "quantum of action" which directly indicates a renunciation of the action principle, the central position of which in the classical description of nature he himself has emphasized on more than one occasion. This principle symbolizes, as it were, the peculiar reciprocal symmetry relation between the space-time description and the laws of the conservation of energy and momentum, the great fruitfulness of which, already in classical physics, depends upon the fact that one may extensively apply them without following the course of the phenomena in space and time. It is this very reciprocity which has been made use of in a most pregnant way in the quantum-mechanical formalism. As a matter of fact, the quantum of action appears here only in relations in which space-time co-ordinates and momentum-energy components, which are canonically conjugate quantities in the Hamiltonian sense, enter in a symmetrical and reciprocal manner. In addition, the analogy between optics and mechanics, which has proved to be so fruitful for the recent development of the quantum theory, depends intimately upon this reciprocity.

It lies in the nature of physical observation, nevertheless, that all experience must ultimately be expressed in terms of classical concepts, neglecting the quantum of

action. It is, therefore, an inevitable consequence of the limited applicability of the classical concepts that the results attainable by any measurement of atomic quantities are subject to an inherent limitation. A profound clarification of this question was recently accomplished with the help of the general quantum-mechanical law, formulated by Heisenberg, according to which the product of the mean errors with which two canonically conjugate mechanical quantities may be simultaneously measured can never be smaller than the quantum of action. Heisenberg has rightly compared the significance of this law of reciprocal uncertainty for estimating the self-consistency of quantum mechanics with the significance of the impossibility of transmitting signals with a velocity greater than that of light for testing the self-consistency of the theory of relativity. In considering the well-known paradoxes which are encountered in the application of the quantum theory to atomic structure, it is essential to remember, in this connection, that the properties of atoms are always obtained by observing their reactions under collisions or under the influence of radiation, and that the above-mentioned limitation on the possibilities of measurement is directly related to the apparent contradictions which have been revealed in the discussion of the nature of light and of material particles. In order to emphasize that we are not concerned here with real contradictions, the author suggested in an earlier article the term "complementarity". In consideration of the above-mentioned reciprocal symmetry which occurs already in classical mechanics, perhaps the term "reciprocity" is more suitable for expressing the state of affairs with which we are dealing. At the conclusion of the paper referred to, it was pointed out that a close connection exists between the failure of our forms of perception, which is founded on the impossibility of a strict separation of phenomena and means of observation, and the general limits of man's capacity to create concepts, which have their roots in our differentiation between subject and object. Indeed, the epistemological and psychological questions which arise here lie perhaps outside the range of physics proper. Yet, on this special occasion, I should like to be permitted to go somewhat more deeply into these ideas.

The epistemological problem under discussion may be characterized briefly as follows: For describing our mental activity, we require, on one hand, an objectively given content to be placed in opposition to a perceiving subject, while, on the other hand, as is already implied in such an assertion, no sharp separation between object and subject can be maintained, since the perceiving subject also belongs to our mental content. From these circumstances follows not only the relative meaning of every concept, or rather of every word, the meaning depending upon our arbitrary choice of view point, but also that we must, in general, be prepared to accept the fact that a complete elucidation of one and the same object may require diverse points of view which defy a unique description. Indeed, strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application. The necessity of taking recourse to a complementary, or reciprocal, mode of description is perhaps most familiar to us from psychological problems. In opposition to this, the feature which characterizes the so-called exact sciences is, in general,

the attempt to attain to uniqueness by avoiding all reference to the perceiving subject. This endeavour is found most consciously, perhaps, in the mathematical symbolism which sets up for our contemplation an ideal of objectivity to the attainment of which scarcely any limits are set, so long as we remain within a self-contained field of applied logic. In the natural sciences proper, however, there can be no question of a strictly self-contained field of application of the logical principles, since we must continually count on the appearance of new facts, the inclusion of which within the compass of our earlier experience may require a revision of our fundamental concepts.

We have recently experienced such a revision in the rise of the theory of relativity which, by a profound analysis of the problem of observation, was destined to reveal the subjective character of all the concepts of classical physics. In spite of the great demands that it makes upon our power of abstraction, the theory of relativity approaches, in a particularly high degree, the classical ideal of unity and causality in the description of nature. Above all, the conception of the objective reality of the phenomena open to observation is still rigidly maintained. As Einstein has emphasized, the assumption that any observation ultimately depends upon the coincidence in space and time of the object and the means of observation and that, therefore, any observation is definable independently of the reference system of the observer, is, indeed, fundamental for the whole theory of relativity. However, since the discovery of the quantum of action, we know that the classical ideal cannot be attained in the description of atomic phenomena.

In particular, any attempt at an ordering in space-time leads to a break in the causal chain, since such an attempt is bound up with an essential exchange of momentum and energy between the individuals and the measuring rods and clocks used for observation; and just this exchange cannot be taken into account if the measuring instruments are to fulfil their purpose. Conversely, any conclusion, based in an unambiguous manner upon the strict conservation of energy and momentum, with regard to the dynamical behaviour of the individual units obviously necessitates a complete renunciation of following their course in space and time. In general, we may say that the suitableness of the causal space-time mode of description for the ordering of our usual experiences depends only upon the smallness of the quantum of action relative to the actions with which we are concerned in ordinary phenomena. Planck's discovery has brought before us a situation similar to that brought about by the discovery of the finite velocity of light. Indeed, the suitability of the sharp distinction between space and time, demanded by our senses, depends entirely upon the smallness of the velocities with which we have to do in daily life compared with the velocity of light. In fact, in the question of the causality of atomic phenomena, the reciprocal character of the results of measurements may no more be neglected than can their relativity in the question of simultaneity.

In considering the resignation with regard to the desires for visualization which give our whole language its character, to which we are compelled by the situation discussed above, it is very instructive that already in simple psychological experiences we come upon

fundamental features not only of the relativistic but also of the reciprocal view. The relativity of our perception of motion, with which we become conversant as children when travelling by ship or by train, corresponds to common-place experiences on the reciprocal character of the perception of touch. One need only remember here the sensation, often cited by psychologists, which every one has experienced when attempting to orient himself in a dark room by feeling with a stick. When the stick is held loosely, it appears to the sense of touch to be an object. When, however, it is held firmly, we lose the sensation that it is a foreign body, and the impression of touch becomes immediately localized at the point where the stick is touching the body under investigation. It would scarcely be an exaggeration to maintain, purely from psychological experiences, that the concepts of space and time by their very nature acquire a meaning only because of the possibility of neglecting the interaction with the means of measurement. On the whole, the analysis of our sense impressions discloses a remarkable independence of the psychological foundations of the concepts of space and time, on the one hand, and the conceptions of energy and momentum, based upon actions of force, on the other hand. Above all, however, this domain, as already mentioned, is distinguished by reciprocal relationships which depend upon the unity of our consciousness and which exhibit a striking similarity with the physical consequences of the quantum of action. We are thinking here of well-known characteristics of emotion and volition which are quite incapable of being represented by visualizable pictures. In particular, the apparent contrast between the continuous onward flow of associative thinking and the preservation of the unity of the personality exhibits a suggestive analogy with the relation between the wave description of the motions of material particles, governed by the superposition principle, and their indestructible individuality. The unavoidable influence on atomic phenomena caused by observing them here corresponds to the well-known change of the tinge of the psychological experiences which accompanies any direction of the attention to one of their various elements.

It might still be permitted here briefly to refer to the relation which exists between the regularities in the domain of psychology and the problem of the causality of physical phenomena. When considering the contrast between the feeling of free will, which governs the psychic life, and the apparently uninterrupted causal chain of the accompanying physiological processes, the thought has, indeed, not eluded philosophers that we may be concerned here with an unvisualizable relation of complementarity. Thus, the opinion has often been expressed that a detailed investigation of the processes of the brain, which, although not practicable, is, nevertheless, thinkable, would reveal a causal chain that formed a unique representation of the emotional mental experience. However, such an idealized experiment now appears in a new light, since we have learned, by the discovery of the quantum of action, that a detailed causal tracing of atomic processes is impossible and that any attempt to acquire a knowledge of such processes involves a fundamentally uncontrollable interference with their course. According to the above-mentioned view on the relation between the processes in the brain and the psychical

experiences, we must, therefore, be prepared to accept the fact that an attempt to observe the former will bring about an essential alteration in the awareness of volition. Although, in the present case, we can be concerned only with more or less fitting analogies, yet we can hardly escape the conviction that in the facts which are revealed to us by the quantum theory and lie outside the domain of our ordinary forms of perception we have acquired a means of elucidating general philosophical problems.

I hope that the special occasion will excuse a physicist for venturing into a foreign field. Above all, my purpose has been to give expression to our enthusiasm for the prospects which have been opened up for the whole of science. In addition, it has been my desire to emphasize as strongly as possible how profoundly the new knowledge has shaken the foundations underlying the building up of concepts, on which not only the classical description of physics rests but also all our ordinary mode of thinking. It is above all to this emancipation that we owe the wonderful progress in our insight into the phenomena of nature which has been made during the last generation, a progress far exceeding all the hopes which one ventured to cherish just a few years ago. Perhaps the most distinguishing characteristic of the present position of physics is that almost all the ideas which have ever proved to be fruitful in the investigation of nature have found their right place in a common harmony without thereby having diminished their fruitfulness. In gratitude for the possibilities of research which he has opened up before us, his colleagues celebrate to-day the creator of the quantum theory.