SOVIET PHYSICS USPEHKI VOLUME 66 (1), NUMBER 2 NOVEMBER-DECEMBER, 1958

REMARKS ON BOHR'S ARTICLE ON HIS DISCUSSIONS WITH EINSTEIN

V. A. FOCK

Usp. Fiz. Nauk **66**, 599-602 (December, 1958)

THE paper by Niels Bohr about his discussions with Albert Einstein on the basic problems of atomic physics, which is printed in this issue of "Uspekhi,"* gives a remarkably clear exposition of the physical foundations on which a correct interpretation of quantum mechanics must be based, and Bohr's paper is of exceptionally great interest in this connection.

With extraordinary cogency, using many simple examples, and without any mathematics except the Heisenberg relations, he demonstrates the limitations of the "classical" way of describing phenomena, i.e., the description in which phenomena are dealt with "by themselves," apart from the means of observation. The possibility of a description of atomic phenomena "by themselves" is analyzed by Bohr on the basis of the Heisenberg relations, in virtue of which the manifestation of different properties of an atomic object in general depends on the use of different experimental conditions, which may be mutually exclusive. Bohr denotes this state of affairs by the term "complementarity"; in explaining this term Bohr says (page 210*) that he understands it "in the sense that only the totality of the phenomena exhausts the possible information about the objects."

An extremely important and indisputably correct point made by Bohr is that classically described apparata play an indispensable part in our knowledge about microscopic objects. Bohr formulates this position in the following words (page 209): "however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms."

This deeply dialectical proposition of Bohr's must unquestionably lie at the foundation of every interpretation of quantum mechanics.

In reading the works of Bohr (in particular the paper printed here) one nevertheless gets the impression that his point of view is in some ways a onesided one. In fact, all of Bohr's efforts are directed to the explanation of the limitations of the old classical concepts, and not to the explanation of the new concepts introduced by quantum mechanics. A formal sign of this onesided approach is that out of the whole apparatus of quantum mechanics Bohr uses only the Heisenberg relations. This cannot simply be due to the effort to make the exposition elementary: even in the most elementary exposition one can and should say something also about the new concepts, and not only show the limitations of the old ones. It seems to us that the point here is the role that Bohr ascribes to the apparatus of quantum mechanics. Bohr mentions it only in passing, and mainly in order to emphasize its supposedly exclusively symbolic character. According to Bohr the mathematical symbols of quantum mechanics, unlike the mathematical symbols of classical physics, do not in themselves possess physical meaning, but serve only as an "adequate tool for the complementary mode of description," as Bohr says in another of his papers.[1] Actually it is scarcely possible that Bohr believes that the mathematical apparatus of quantum mechanics serves only for the coordination of instrument readings obtained in measurements, but this point inevitably arises when one peruses his writings. At any rate, such a point of view would be incorrect. It is unquestionable that quantum mechanics (like any other physical theory) provides, along with other things, a way of correlating the readings of instruments involved in measurements. But this is not its basic significance. The task of a physical theory is always to describe the properties of physical objects in their relations to the external world. Certainly neither Bohr himself nor any other physicist denies the objectivity of such properties of atomic bodies as the charge, the mass, the spin, the degrees of freedom, the form of the wave equation in a given field, the law of interaction with other particles, and so on. Not only are these properties objective, but also they can be abstracted from the apparatus and ascribed to the objects themselves.

The main efforts of Bohr are directed, as we have said, to the explanation of the state of affairs in atomic physics which he denotes by the term "complementarity." Admitting all the necessity and importance of this explanation, we can still regret that Bohr does not show the way out of this situation, does not say what the new primary con-

*Page references in the translation are to Albert Einstein: Philosopher-Scientist, edited by P. A. Schilpp, New York 1951. The Bohr article referred to begins on p. 201. (Translator).

cepts (physical, intuitive, and not merely symbolical, concepts) are that must take the place of the classical concepts, and does not emphasize the unlimited possibilities of improving the accuracy of our description of atomic objects by means of new concepts. Not only the limitation inherent in the description of phenomena "by themselves," in abstraction from the means of observation (complementarity) is of philosophical importance, but also the constructive features of quantum mechanics and the new primary concepts associated with it.

In our opinion, these primary concepts, on which atomic physics can be constructed, are the following: relativity to the means of observation, the difference between the potentially possible and the actually observed (or between prognosis and fact), and, finally, the concept of probability as a numerical measure of the potentially possible. The apparatus of quantum mechanics, which has as its direct task to serve for the calculation of this numerical measure, is at the same time a means for the introduction of new abstractions and new, more refined physical concepts, and for the more accurate description of the properties of atomic objects on the basis of these new concepts. In connection with the introduction of the new primary concepts the concept of causality also receives a new formulation.

We shall not enter here upon an exposition of our point of view on these questions, since we have done so elsewhere.[4] We wish only to explain what we have in mind when we speak of new primary physical concepts.

In his writings Bohr repeatedly emphasizes the necessity of considering an experiment as a whole, without dividing it into stages. Bohr assumes that we can speak of a definite phenomenon only when we have a completed experiment, and therefore proposes to consider only such experiments. Of course a definite answer to the question for which the particular experiment has been set up can be obtained only when this experiment has been completed. Nevertheless Bohr's demand that we consider only completed experiments seems to us too categorical, since it leaves no room for quantum-mechanical abstractions. Only the division of an experiment into stages,* and only an arrangement of the experiment in such a way that the choice of the last stage, the stage of measurement, remains free, actually makes it possible to introduce the concept of the state of the object, which is a fundamental concept for the quantum mechanics. The situation that occurs with such an arrangement of an experiment at the time when just the choice of the last stage remains free can be called a "conceptually interrupted experiment." In our opinion only the discussion of an uncompleted, conceptually interrupted experiment enables us to introduce the concept of the wave function.*

In fact the key points in the discussion between Bohr and Einstein arise in the discussion of just such conceptually interrupted experiments, and this is understandable, since it is just in these cases that the peculiarities of quantum physics that distinguish it from classical physics are most strikingly manifested. The category of conceptually interrupted experiments includes also both the experiments proposed by Einstein, namely the experiment in which one could measure either the energy of a quantum or the time of its emergence, and the experiment in which one could measure either the coordinate of a particle or its momentum (cf. pp. 219 and 229). Thus Bohr himself does not strictly observe his requirement that one consider only a completed experiment. The pronouncements made by Bohr on this point are to be understood more correctly not in the sense of a compulsory requirement, but rather in a broader sense, as a reminder of the fact that one cannot always carry out a division of an experiment into stages, and that in cases in which this cannot be done the concept of the object does not have a definite meaning.

Thus our main comments bear on a certain incompleteness of the article, on the fact that Bohr's brilliant demonstration of the limitations of classical concepts is not accompanied by at least a brief indication of what must replace them. To this main point we may add a few remarks, which are in part, however, only concerned with terminology,

We feel that Bohr has adopted a most unfortunate use of the word "causality," which as it were allows causality and complementarity to be placed in opposition to each other, and thus leads toward a denial of causality. One must introduce two terms, for example, "Laplacian determinism," which means the belief in the possibility in principle of prognoses of unlimited precision, and the more general term "causality," in the sense of the existence of laws of nature. Laplacian determinism is in fact overthrown by quantum mechanics, but causality is altogether maintained, and one has only to express it in new forms.

*On the division of an experiment into stages see previous papers by the writer,[2,3]

*If we use the concept of "preparation of the object," then we can say that in an "uncompleted" experiment we have to do with an object prepared in a definite way. The concept of the wave function has indeed always been associated with such an object.

Another unfortunate term used by Bohr is "uncontrollable interaction." Essentially one is speaking here not about an interaction in the proper sense of the word, but about the logical interconnection between the quantum and classical modes of description at the nexus between the part of the system that is described qunatum-mechanically (the object) and the part that is described classically (the instrument). In the passage from the quantum language to the classical there is as it were a loss of precision; when Bohr says that an uncontrollable interaction occurs between the object and the instrument, he undoubtedly has just this in mind. Taken literally, however, the term "uncontrollable interaction" leads to misunderstanding: surely every physical process is knowable, and consequently is also accessible to control. It may be supposed that this term arose from the attempt to use classical concepts outside their domain of validity.[3]

One also finds in Bohr's article imprecise expressions like the following: "the knowledge of the position of the diaphragm" (page 217) or "our knowledge of the adjustment of the clock", (page 227), and so on, whereas in actual fact the meaning is not concerned with our knowledge, but with objective facts, for example, with the accuracy to which we can establish a correspondence between the position of the diaphragm and a scale fixed in the laboratory, or between the readings of a given clock and those of the laboratory clock. In such expressions "we" seem to be identifying ourselves with the "laboratory". Therefore it is not to be supposed that the use of such expressions reflects any subjectivity in Bohr's point of view; without question this is simply carelessness, and there is no real need to comment on such imprecise expressions.

In conclusion we would like to point out that all, or nearly all, of the remarks made here were the subject of personal discussions between Bohr and the writer at the time of the writer's visit to Copenhagen in February and March of 1957. As a result of the series of discussions (during which we always had before us the original of the paper of Bohr which is republished here) Bohr evidently agreed with many of the writer's comments, and declared from the very beginning that he is an opponent of positivism. Bohr's emendations to his original statements have been expressed in a paper "Quantum Physics and Philosophy," which will be published in the next (January) issue of Uspekhi Fizicheskikh Nauk.

---

[1] N. Bohr, Dialectica **1**, 312 (1948).

[2] V. A. Fock, Usp. Fiz. Nauk **45**, 3 (1951).

[3] V. A. Fock, Чехословацкий физический журнал (Czechoslov. Phys. J.) **5**, 436 (1955).

[4] V. A. Fock, Usp. Fiz. Nauk **62**, 461 (1957).

Translated by W. H. Furry