Niels Bohr, Complementarity, and Realism

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The so-called "orthodox" interpretation of quantum physics attributed to Niels Bohr is commonly regarded as abandoning realism. I have already opposed this view elsewhere (Folse 1985) but partially in response to criticism of my position (Shimony 1985), here I propose to relate Bohr's realism to recent contributions to the realism debate given by Hacking (1983), Cartwright (1983), and Ellis (1985). Specifically, I argue that Bohr's complementarity viewpoint requires a causal entity realism. Furthermore, labeling Bohr an anti-realist with respect to theories is misleading because it assumes the correspondence theory of truth that Bohr holds quantum theory forces us to reject.

1. Realism, Metaphysics, and Quantum Physics

Although there are many realist views, I take the root of realism to be the quest for knowledge about the reality producing the phenomena we experience. It is realism in this sense that Bohr defended and that makes science significant to metaphysics. The customary realist presupposition that knowledge about that reality requires the "truth" of theoretical statements to reside in a correspondence between at least some terms in these statements and the properties of entities to which these terms refer is based on the "spectator theory of knowledge".

Given this conception of realism, the reason for its apparent incompatibility with quantum physics is obvious: a realist who believed the theories of classical physics knew what the reality that was claimed to lie behind the phenomena was suppose to be like. One could interpret classical theory by a model of entities possessing properties "corresponding" to the parameters defining the system's classical mechanical state as it exists isolated from observation. Most importantly these same properties of the model could be regarded as corresponding to properties of real entities that cause the observable phenomena classical theory is assumed to explain. Thus classical theory could be interpreted by a model allowing the realist to have a more or less concrete idea of what reality behind the phenomena is like. Already in the nineteenth century the tension between the growth of physical theory and this classical ontology made the anti-realist's

PSA 1986, Volume 1, pp. 96-104

outlook more plausible, but the realist's image of physics was essentially left dangling without an ontological support as soon as the consequences of the quantum revolution became established parts of physics.

From this characterization of the problem, the defense of realism in quantum physics would seem to require developing an ontology of what reality is like behind the phenomena quantum physics intends to describe. This would replace the no longer acceptable ontology that once supported the realist's understanding of classical physics. However, instead of such an overtly metaphysical approach, philosophers of science have become entangled in the problems of theoretical reference. As is well known the quantum theoretical formalism not only precludes a classical model interpretation, but also has mightily resisted any alternative based on correspondence lines. Thus the realist who accepts the correspondence theory of truth confronts the infamous problem of the reference of the state function and its illegitimate offspring, the reduction of the wave-packet. What does the Schrodinger function refer to? How can the quantum mechanical object be in a superposition of states? Is the "reduction of the wave packet" a strange physical event taking place in observing interactions? Does the projection postulate describe something that happens in reality, or is it an artifact of our theoretical formalism? Reflection on these questions has led one philosopher after another away from realism into anti-realism.

The attempt to characterize Bohr's position within this debate is frustrated by the fact that he totally ignores all these questions. Furthermore, complementarity does not easily fit into either of the philosopher's categories of "realism" or "anti-realism". No doubt many are only too willing to shoehorn his view into one or the other of these categories, but doing so hardly aids understanding Bohr's position. Given the historical importance of that position, it may even severely distort our understanding of quantum physics. Can it be irrelevant that Bohr had formed his ideas well before anyone had ever heard of the projection postulate and the reduction of the wave-packet? Might it not suggest there is something wrong with the philosopher's way of characterizing the issue that Bohr's view cannot be made coherent and consistent? Was Bohr simply mistaken to feel, as he told Thomas Kuhn, that "philosophers were very odd people who were really lost"? (Bohr 1962, p. 3). After all, perhaps we are.

2. Why Bohr *Is* a Realist

Bohr's realism appears at his starting point, the description of the physical system of the chemical atom. The young physicist who pioneered the "old" quantum theory of 1913 was committed to the reality of atoms because they were causally responsible for a large variety of phenomena already studied in the laboratory. Even after the "new" quantum theory of 1925-26, in 1929 Bohr begins his presentation of complementarity with the following clear statement of his causal entity realism. First he points out that atomism is essentially a hypothesis about the causes of phenomena:

> Natural phenomena, as experienced through the medium of our senses, often appear to be extremely variable and unstable. To

https://doi.org/10.1086/psaprocbienmeetp.1986.1.193111 Published online by Cambridge University Press

> explain this, it has been assumed, since early times, that the phenomena arise from the combined action and interplay of a large number of minute particles, the so-called atoms, which are themselves unchangeable and stable, but which, owing to their smallness, escape immediate perception. Quite apart from the fundamental question of whether we are justified in demanding visualizable pictures in fields which lie outside the reach of our senses, the atomic theory originally was of necessity of a hypothetical character; and, since it was believed that a direct insight into the world of atoms would, from the very nature of the matter, never be possible, one had to assume that the atomic theory would always retain this character. (Bohr 1929a, pp. 102-103).

But, Bohr continues, the speculative character of this hypothesis has now been overcome by the experimental production of phenomena which are the direct causal effects of the behavior of atoms:

> However, what has happened in so many other fields has happened also here; because of the development of observational technique, the limit of possible observations has continually been shifted. We need only think of the insight into the structure of the universe which we have gained by the aid of the telescope and spectroscope, or of the knowledge of the finer structure of organisms which we owe to the microscope. *Similarly, the extraordinary development in the methods of* experimental physics has made known to us a large number of *phenomena which in a direct way inform us of the motions of* atoms and of their number. We are aware even of phenomena which with certainty may be assumed to arise from the action of a single atom. However, at the same time as every doubt regarding the reality of atoms has been removed and as we have gained a detailed knowledge of the inner structure of atoms, we have been reminded in an instructive manner of the natural limitation of our forms of perception. (Bohr 1929a, p. 103).

One could hardly wish for a clearer statement of causal entity realism: the reality of atoms has been established by experiments which directly cause phenomena that inform us of the existence and behavior of atoms. This is the view espoused by Hacking: "The best kinds of evidence for the reality of a postulated or inferred entity is that we can begin to measure it or otherwise understand its causal powers." (Hacking 1983, p. 274). For Bohr the *existence* of atomic systems is "the given", which theory must describe in a way allowing prediction of those phenomena caused by these entities. Once it was reasonable to be skeptical about the existence of atoms; that is no longer the case. Experiment has put that issue to rest. (*Cf.* Hacking 1983, p. 271-272). Thus Bohr comes onto the stage a clearly convinced realist about atoms.

This approach to realism from the physical analysis of the cause of phenomena is entirely in keeping with Bohr's temper as a natural philosopher/physicist. Heisenberg leaves us the following revealing reminiscence:

> ...his insight into the structure of the theory was not a result of mathematical analysis of the basic assumptions, but rather of an intense occupation with the actual phenomena, such that it was possible for him to sense the relationships intuitively rather than derive them formally.
>
> Thus I understood: knowledge of nature was primarily obtained in this way, and only as the next step can one succeed in fixing one's knowledge in mathematical form and subjecting it to complete rational analysis. Bohr was primarily a

> philosopher, not a physicist, but he understood that natural philosophy in our day and age carries weight only if its every detail can be subjected to the inexorable test of experiment. (Heisenberg 1964, pp. 94-95).

Virtually all who worked with Bohr testify to his remarkable conceptual grasp of the physical processes producing atomic phenomena. Like Hacking, Bohr accepts realism because atomic theory can be used to design experiments which produce phenomena that are explained as the causal effect of the behavior of atomic entities. Bohr's realism was not based on establishing a correspondence between his atomic model which "interprets" the theory and the reality lying behind the phenomenon. Indeed, he repeatedly cautioned against taking the model as a literal representation of the atomic system.

Bohr's disregard for the "problem" of the reduction of the wave-packet is in keeping with his approach to physics that made him instinctively chary of the formalistic approach of the pure mathematics. Heisenberg emphasizes that "...Bohr would not like to say that nature imitates a mathematical scheme." (Heisenberg 1963a, p. 15). He explains this attitude by appeal to Bohr's intuitive realism, contrasting his way of doing physics with the mathematically oriented Dirac:

> ...Bohr was not a mathematically minded man, but he thought about the connection in physics. He was, I would say, Faraday, but not Maxwell.
>
> ...there was a different sort of way of doing physics,...one doesn't bother too much about the mathematical scheme. That is a later trouble. One first tries to see how things are connected - what they really mean. I would say that is really quite contrary against that kind of thing which Dirac does because Dirac starts from extremely nice mathematical schemes and never starts from the connections. This kind of physics which Faraday and Bohr and Ehrenfest tried to do really starts from the connections. Now nature does act in this experiment and, if nature acts this way, must it not act in another experiment that way. How are these things connected? Can we understand the one from the other?... One is forced to think very carefully about what will actually happen in this experiment. How does nature avoid this trouble? (Heisenberg 1963b, p. 30).

Thus Bohr was not much impressed by attempts to arrive at a conception of reality in the quantum domain by arguing from the reduction of the wave-packet. For him the problem was in physics, not in the formalism.

Bohr regarded the heart of the quantum revolution and his new viewpoint of complementarity to be what he called the "quantum postulate", the premise that atomic systems undergo discontinuous changes of state in an interaction. (Bohr 1934, pp. 53-54). Bohr arrives at the quantum postulate by generalizing from empirical studies of atomic interactions. The basis for his conviction is the causal explanation of what has been discovered in the laboratory not any deduction from more "fundamental" theoretical statements. His position parallels Cartwright's realist defense of phenomenological laws, and, like Cartwright he eschews building a model to interpret the formalism and then establishing a representational correspondence between the properties of this model and the properties of a reality that lies behind the phenomena. As Cartwright points out, the attempts to arrive at realism by establishing a correspondence between fundamental theory

https://doi.org/10.1086/psaprocbienmeetp.1986.1.193111 Published online by Cambridge University Press

and a reality behind the phenomena is blocked by the fact that it is not the formalism which provides the function that defines the quantum state of the system; it gives only the equations it must obey. (Cartwright 1983, pp. 163-206). The precise function must be teased out of nature's mysteries by half conceptual and half empirical means at which, according to all testimony, Bohr was an incomparable master.

Bohr not only *is* a realist in his image of physics, but also he *must* be a realist to support his complementarity doctrine. Complementarity holds that different exclusive experimental arrangements produce phenomena which are interpreted as providing "complementary information" about "the same object": "Information regarding the behavior of an atomic object obtained under definite experimental conditions, may, however, according to a terminology often used in atomic physics, be adequately characterized as *complementary* to any information about *the same object* obtained by some other experimental arrangement excluding the fulfillment of the first conditions. Although such kinds of information cannot be combined into a single picture by means of ordinary concepts, they represent indeed equally essential aspects of any knowledge of the object in question which can be obtained in this domain." (Bohr 1939, p. 26 italics mine). The complementarity between such phenomena implies that there is a *same object* which is making different phenomenal appearances in different experimental interactions. Two phenomena cannot be considered complementary evidence about the "same object" unless that "same object" is that which causes the complementary phenomena in the different observational interactions. Without presupposing entity realism, Bohr's basic conclusion that different experimental arrangements provide complementary evidence about the same object would make no sense.

3. Why Bohr *Appears* to Be an Anti-Realist

Bohr maintains the epistemological lesson of complementarity is the consequence of making the quantum postulate consistent with the rest of physical theory. The discontinuity in change of state rather than any indeterminacy of the classical parameters was the touchstone of all his arguments. Traditional realism's acceptance of the spectator theory presupposes that empirical knowledge must represent its object as it exists apart from the observational interaction which is the basis of that knowledge. Even classically observation requires interaction, but that classical interaction either is negligible or because it takes place continuously in phase space can be taken into account by using theory to determine the state of the object existing apart from observation. The quantum postulate makes this impossible, leading Bohr to conclude that the object of empirical knowledge must be *interaction*, not some independently existing reality. Thus the quantum postulate is incompatible with the spectator theory of knowledge, for the latter must assume that observation in no uncontrollable way changes the observed object. Nevertheless, although the quantum postulate requires abandoning the goal of representing the object apart from observation, at the same time by making the object of knowledge interaction, it commits complementarity to causal entity realism.

Consequently, Bohr's image of physics demands that the object in the "description of nature" is not an independent reality. Instead theory

https://doi.org/10.1086/psaprocbienmeetp.1986.1.193111 Published online by Cambridge University Press

functions in "interpreting" phenomena as interactions between atomic systems and observing instruments. But this interpretation of phenomena requires defining the state of the system before the interaction. When we raise the question of the reference of the function defining this state, Bohr appears on the anti-realist side of the philosopher's ledger, for he holds that the theoretical characterization of an isolated system is only an "idealization" or "abstraction" used for interpreting the phenomena in which an atomic entity is "observed".

> ...it would scarcely seem justifiable, in the case of the interaction problem, to demand visualization by means of space-time pictures. In fact all our knowledge concerning the internal properties of atoms is derived from experiments on their radiation and collision reactions, such that *the interpretation of experimental facts ultimately depends on the abstractions* of radiation in free space and free material particles. Hence our whole space-time view of physical phenomena, as well as the definition of energy and momentum depends ultimately on these *abstractions*. In judging the application on these auxiliary ideas, we should only demand inner consistency.... (Bohr 1927, p. 55, italics mine).

To interpret phenomena we use wave or particle concepts to form a "space-time picture" of the atomic object apart from the observing system. But these pictures refer to "abstractions" because interpreting an experimental phenomenon as an observation determining some property of the system requires that the system interact in a discontinuous way with the observing instruments. As expressed formally in the uncertainty relations, the attempt to form a space-time picture of the system *as observed* is impossible, because the application of the space-time concepts must stand in a complementary relationship to the causal interpretation of the interaction:

> ...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 fulfill their purpose. Conversely, any conclusion, based in an unambiguous manner upon the strict conservation of energy and momentum, with regard to the dynamical behavior of the individual units obviously necessitates a complete renunciation of following their course in space and time. (Bohr 1929b, p. 98).

To interpret the interaction as an observation, we must use the dynamical conservation principles to provide a causal account of the interaction:

> In particular it should not be forgotten that the concept of causality underlies the very interpretation of each result of experiment, and that even in the coordination of experience, one can never, in the nature of things, have to do with well-defined breaks in the causal chain. The renunciation of the ideal of causality in atomic physics which has been forced on us is found logically only on our not being any longer in a position to speak of the autonomous behavior of a physical object, due to the unavoidable interaction between the object and the measuring instruments which in principle cannot be taken into account, if these instruments according to their purpose shall allow the

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unambiguous use of the concepts necessary for the description of experience. (Bohr 1937, pp. 293-294).

Thus although we must "renounce" the classical conjunction of causal and space-time modes of description, experimental phenomena are "interpreted" using the classical space-time and dynamical concepts in a way which allows us to describe them as the causal result of the behavior of the atomic object. The two modes of description are complementary.

Although the theoretical formalism cannot be understood as representing the independently existing object, its function is to interpret the experimental phenomena in a way that must presuppose the reality of the microsystem causing the phenomena. Acceptance of the formalism's definition of the quantum state rests not on a correspondence between a model which interprets the theory and an independent reality, but on pragmatic grounds: it allows interpretation of experiments as causal interactions in which atomic objects reveal how they behave. I take this to be the view presented by Ellis in his pragmatist defense of realism: "Science aims to provide the best possible explanatory account of natural phenomena; and acceptance of a scientific theory involves the belief that it belongs to such an account." (Ellis 1985, p. 51). I suspect that most physicists would regard such causal/pragmatic grounds to which Hacking and Ellis appeal to be far more robust than the pale theoretical abstraction which the "theory-realist" so covets.

Thus this "instrumentalist" tendency in complementarity could support characterizing Bohr as an anti-realist with respect to theories. But this form of anti-realism does not compromise Bohr's robust realism with respect to the reality of atomic systems. Hacking and Cartwright both defend a similar combination of realism with respect to entities and anti-realism with respect to theories. The realists' view that the phenomena on which atomic theory is accepted do inform us about the properties and behavior of real atomic systems *in interaction* is not inconsistent with the anti-spectator view that the theoretical definition of the state of an isolated system does not correspond to an entity existing *apart from phenomena* but is an "abstraction" necessary for interpreting experiments. But the realist would like to add that accepting the causal account provides good reason for accepting as "true" the theory which makes possible this interpretation of phenomena. As Ellis his nicely argued, the casualty of such a conjunction of doctrines need not be realism (indeed it cannot be in Bohr's case); instead it must be the correspondence theory of truth. (Ellis 1985, pp. 67-73).

Consequently, Bohr's appearance as an anti-realist with respect to theories, is due to defining "realism" in terms of a correspondence theory of the truth of theoretical statements. Identifying Bohr as an anti-realist results from how philosophers raise the question of realism rather than how Bohr saw his outlook. But if "realism about theories" is the construct of our dominant epistemology, and Bohr does not accept this epistemology, then do we not mischaracterize him when we label his view anti-realist? Bohr spoke in terms of "objective communication" rather than "truth": "Every scientist...is constantly confronted with

https://doi.org/10.1086/psaprocbienmeetp.1986.1.193111 Published online by Cambridge University Press

the problem of objective description of experience, by which we mean unambiguous communication." (Bohr 1955, pp. 67-68). It is because his interactionist account of observation forces him to reject the spectator theory of knowledge, that "objectivity" for him has only the pragmatic meaning of unambiguous communicability. Since he earnestly argued quantum theory provides the only possible scientific knowledge of the atomic domain, the obvious way to make his view coherent is to replace the correspondence notion of truth with a pragmatic one. Consequently, reading Bohr as an anti-realist involves misunderstanding his view of the relationship between theory, atomic systems, and experimental phenomena. Bohr never tried to answer whether complementarity is anti-realist or not because that question arises from looking at physics in a way that he simply did not see it. Perhaps it is precisely because philosophers keep seeing physics their way, that to Bohr they appeared to be those "very odd people who really were lost". Perhaps after all, theoretical statements simply are not supposed to represent objects behind the phenomena; that is not how we find out about the reality which the realist so yearns for.

If Ellis, Hacking, Cartwright, and I would add Bohr, are right, the basis for the realists' beliefs about the reality behind the phenomena is the causal stories physics enables us to tell about how real entities interact with the observing apparatus to produce the phenomena which theory interprets as informative of their behavior. The grounds for holding a theory to be true must be the manner in which it allows us to tell causal stories that are consistent, comprehensive, and predictive of novelty regarding those phenomena which form the empirical support for the theory. Classical physics provided good historical reasons why philosophy was once led to define theoretical truth as the representational correspondence between a model interpreting the theory and a reality behind the phenomena, but when we accept quantum theory there are good scientific reasons why it should no longer be so misled.

Notes

[1]Arguing primarily the case against realism with respect to theories, Cartwright refers to herself as an anti-realist, while arguing primarily for realism about entities, Hacking and Ellis refer to themselves as "realists". There is no real disagreement here, but if one rejects a correspondence theory of truth, as do Hacking and Ellis, the anti-realist label, even with respect to theories, is no longer warranted. See Section 3 below.

[2]Of course the empiricist anti-realist wants to show science is *not* significant to metaphysics; whereas for realists this is what makes science interesting. Ultimately the difference may be one's philosophical temperament.

[3]Shimony reveals the commitment to the spectator theory in his criticism of my interpretation, when he asks, "What are the intrinsic properties of the atomic object?" (1985, p. 108). Bohr claims that the "epistemological lesson" of quantum physics concerning "the description of nature" reveals a seriously different image of science.

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https://doi.org/10.1086/psaprocbienmeetp.1986.1.193111 Published online by Cambridge University Press