

Knowledge and Description: Bohr's Epistemology¹

Niels Bohr had an interest in philosophical problems that lasted from his youth to his death. Indeed, when in 1949 he wrote his article for Paul Schilpp's book honoring Einstein, Bohr characterized the life-long discussion with his fellow physicist in this way:

From the very beginning the main point under debate has been the attitude to take to the departure from customary principles of natural philosophy characteristic of the novel development of physics which was initiated in the first year of this century by Planck's discovery of the universal quantum of action².

Bohr conceived of much of the prose work that he produced from 1925 to 1962 as being natural philosophy, and it seems fair to say that during this period it was difficult, as it has been from time to time throughout the history of physics, to decide where the line between science and philosophy should be drawn.

In order to emphasize this point, and to stress the extent to which Bohr understood quantum physics to be breaking fresh

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² Niels Bohr, *Atomic Physics and Human Knowledge*, New York: John Wiley and Sons, Inc., 1958, pp. 32-33.

philosophical ground, let me quote from him once more. In 1937, he argued that

(...) the whole conceptual structure of classical physics, brought to so wonderful a unification and completion by Einstein's work, rests on the assumption, well adapted to our daily experience of physical phenomena, that it is possible to discriminate between the behaviour of material objects and (...) their observation. For a parallel to the lesson of atomic theory regarding the limited applicability of such customary idealizations, we must in fact turn to quite other branches of science, such as psychology, or even to that kind of epistemological problems with which already thinkers like Buddha and Lao Tse have been confronted, when trying to harmonize our position as spectators and actors in the great drama of existence³.

In this paper, I shall try to explain the philosophical problems that Bohr felt had been exposed by the discovery of the "quantum of action", and by the emergence of the quantum theory that arose in large part as a result of his efforts. I hope you will see, as Bohr saw so clearly, just how central these problems are. I won't have time to make the case here, but my own view is that we have not yet fully digested the message brought to us by Bohr's "Copenhagen Interpretation" of Quantum Mechanics, and I suspect that it will finally prove to be every bit as revolutionary as Bohr thought it was.

It is important, before we get into the philosophical problems posed by quantum mechanics, to understand at least the broadest outline of the physics. To begin with, let me remind you of the sort of behavior that traditional Newtonian physics, and probably common sense also, would lead us to expect of sub-atomic particles. Here is a typical "classical" law of motion:

$$x = x_0 + v_0 (t - t_0) + \frac{1}{2} a (t - t_0)^2.$$

In this equation we assume that whatever acceleration the object is it is constant throughout the period we are examining. If the present time is designated by t_0 , the equation tells us how to

³ Ibidem, pp. 19-20.

determine the position of a moving object at any later time t , provided only that we know its present position, its present velocity, and its acceleration.

If we apply our classical expectations or intuitions to the realm of sub-atomic particles, we may of course be prepared to find that slightly different equations apply there. After all, it is a new domain. But we are bound to anticipate that the equations will have some features in common with the traditional ones. In particular, we are bound to expect that we will be able to predict the future position of a particle, given a specification of the relevant present variables. Sub-atomic particles in motion, we anticipate, will go only to those places that the laws of physics allow them to go to. They will not jump about at random or for no reason at all. If we know where they are now, and if we know what they are doing, then the correct laws of physics would tell us where to look for them at any arbitrary time in the future.

But how would you get an accurate measure of the position, say, of a particle in motion (they appear always to be in motion, as it happens)? Well, you might set up an apparatus that will note the presence of the particle when it bangs into a detecting device – a photographic plate, for example. This kind of set-up will tell you where the particle is, with as much precision as you care to put into the matter. But, precisely to the extent that you take precautions that the photographic plate doesn't move when the particle bashes into it, to that extent you disturb the velocity – or momentum – of the thing. So now that you've got the position of the particle, you've made it impossible to figure out what its momentum was. Experiments may be designed, on the other hand, to measure the momentum of a particle as precisely as may be desired, but the kinds of techniques required to do that make it more or less impossible, depending upon the degree of precision with which the momentum gets measured, to determine the position of the particle. At the subatomic level, therefore, one cannot determine the simultaneous position and momentum of a moving object. Thus no prediction can be made about subsequent positions and moments. This is the sense in which it is said

that the quantum domain is fundamentally indeterminate or unpredictable, as regards such "complementary" characteristics as position and momentum.

Physics is physics, though, and the people who were first bringing these facts to light in the first three decades of this century - people like Niels Bohr, Werner Heisenberg and their colleagues throughout the world of physics - were not satisfied with a mere statement of the impossibility of certain joint determinations of the values of classical variables like position and momentum. By far the most striking theoretical achievement in the 1920's was an objective, quantitative statement of this situation. I'm speaking, of course, about Heisenberg's uncertainty principle, also called the principle of indeterminacy:

$$\Delta x \Delta p \approx \hbar; \text{ or } \Delta t \Delta E \approx \hbar$$

In this formula, Δx represents the degree of precision with which the position of an object is determined, Δp represents the degree of precision for the momentum. The first equation says that these two degrees of precision must vary reciprocally: the greater the precision in determining position, the less is the precision with which momentum can be determined. What is startling is that this variation is a function of a particular constant, \hbar , which is called "Planck's constant". The equation on the right shows that this complementarity holds not only between position and momentum, but also between time (t) and energy (E). Bohr argued that the principle of indeterminacy (or uncertainty principle, or complementarity principle) held between any attempt to determine spatio-temporal properties of a system, on the one hand, and any attempt to examine the system in the light of conservation principles, on the other.

You might think that this is just a clever mathematical trick, but keep in mind that the constant in question that relates these things - Planck's constant, \hbar - is no arbitrary number thrown in just for the purpose of relating measurements to one another. It is the so-called "quantum of action", discovered by Max Planck at the very beginning of this century's remarkable progress in un-

derstanding the fine structure of the physical universe. It was discovered in the context of Planck's efforts to explain some curious radiation-emitting properties of ideal solids (or "black bodies" or "cavity radiators"). Planck found that he could explain these features quite elegantly on the assumption that 1) an object in motion cannot have just any energy; only energies that are values of the following equation being possible:

$$E = n\hbar\nu,$$

where ν is the frequency of oscillation of the energetic object, n is some whole number (the "quantum number") and \hbar is $(6.63 \times 10^{-34} \text{ joule sec})/2\pi$; and 2) the only changes in energy (or transitions) that are possible can be understood as changes in the quantum number n . Long before the development of Heisenberg's uncertainty principle, therefore, the existence of \hbar , the quantum of action, had been found to be responsible for some crucial features of the world. Just by way of noting the importance of Planck's constant, let me mention that among the features which could be explained only by accepting the existence of the quantum of action were such things as the stability of the properties of the elements, and (perhaps most important) the very fact that electrons do not collapse into the nucleus of their atoms (as they would, if the quantum of action did not make continuous variations in energy impossible).

What is important here is not so much the historical picture of physics in the early moments of the twentieth century, but just this: Heisenberg and Bohr were able to show not only that simultaneous determinations of such complementary variables as position and momentum were in principle impossible, but that one can state this fact in a mathematically precise, experimentally verifiable way, referring only to a constant which by the 1920's had a wonderful pedigree: Planck's quantum of action. In other words, one could be certain about the inevitability of uncertainty. In 1927, Bohr wrote

(...) any measurement which aims at tracing the motions of the elementary particles introduces an unavoidable interference with the

course of the phenomena and so includes an element of uncertainty which is determined by the magnitude of the quantum of action. This indeterminacy exhibits, indeed, a peculiar complementary character which prevents the simultaneous use of space-time concepts and the laws of conservation of energy and momentum (...) ⁴.

The upshot of all this is, first, that it is impossible to get the information that one would have to have in order to make the kind of predictions about the future behavior of a sub-atomic particle that classical physics would lead us to think we should be able to make. Not only is it impossible for any laws of physics to predict such future behavior of particles, the laws of physics are what tell us that this is so. But think what this means. If we cannot talk meaningfully about predicting the total behavior of the systems we are examining, we are abandoning a key feature of traditional physics: its effort to give deterministic or causal accounts of its domain. According to Bohr, we abandon causal accounts when we enter the sub-atomic world. The expectation we started out with, that physics should be able completely to specify what will happen next in a system, on the basis of what is happening now, cannot be satisfied at the sub-atomic level. Causal accounts of phenomena can be meaningful only when those phenomena are very large in comparison with the quantum of action. They are not available at the quantum level.

Remember, though, that all of this results from the fact that attempts to observe a system inevitably interfere with that system. Putting the matter this way allows us to see the implications of quantum mechanics in a new light. How do we define, with precision, the system we are observing? How do we distinguish, even, between the system that we are observing and the instruments we use to perform the observation? Bohr was fond of arguing that quantum mechanics shows that we cannot make such a distinction in any but an imprecise way. He pushed this thesis as far as it can be made to go, saying such things as that

⁴ Niels Bohr, *Atomic Theory and the Description of Nature*, Cambridge: The University Press, 1934, p. 11.

(...) the notion of complementarity serves to symbolize the fundamental limitation, met with in atomic physics, of the objective existence of phenomena independent of the means of their observation"⁵.

Just what the phenomenon is may be problematic at the quantum level.

Such remarks, of course, raise questions that seem even more perplexing. The entire "scientific" attitude has, traditionally, presupposed the possibility of "objectively" observing phenomena that are neatly and cleanly separable from the observer. It has always been apparent that an inability to prevent uncontrollable external variables from corrupting an examined system would preclude any precise understanding of what was going on in the system. That is why, people have thought, it is so difficult – if not impossible – to have confidence in the possibility of "sciences" of human behavior. In anthropology, as an example, one cannot study a group of people without affecting it in some way. The very fact that a person or group is being studied is likely to change the behavior of that person or group from what it would have been had it not been studied. Such problems are to be met with in all the social sciences. As Bohr himself pointed out repeatedly, one understanding of the objectives of the biological sciences would suggest that they, too, are subject to the same kind of problem: if the objective is to understand the micro-details of life, one is faced with the likelihood that examining a living creature closely enough to get the answers might require procedures that would kill it, thus destroying the particular properties of the creature that were the objects of the inquiry in the first place.

Physics, though, seemed traditionally to be immune from these problems. Here, anyway, the inquirer could control the experiments in such a way as to avoid the sloppiness that was inevitable in other areas of inquiry. With the development of quantum mechanics, it becomes clear that this apparent superiority of physics to other disciplines in this regard had been a function

⁵ Niels Bohr, *Atomic Physics...*, op. cit., p. 5.

strictly of the relative refinement of the implements of observation vis a vis the things observed. In particular, it becomes apparent that there is an absolute limit to the ability to treat phenomena as independent of any act of observation. As Bohr has said,

(...) the finite magnitude of the quantum of action prevents altogether a sharp distinction being made between a phenomenon and the agency by which it is observed⁶;

(...) the concept of observation is in so far arbitrary as it depends upon which objects are included in the system to be observed (...) for every particular case it is a question of convenience at which point the concept of observation involving the quantum postulate (...) is brought in⁷;

and finally, for the boldest statement of the thesis,

Strictly speaking, the idea of observation belongs to the causal space-time way of description⁸.

Since the universal applicability of the "causal space-time way of description" has been called into questions by quantum mechanics, this would imply that similar questions are raised about the universal applicability of the very idea of observation.

It was difficult, if not quite impossible, to get used to the idea, suggested by Einstein a bit earlier in the twentieth century, that our "common sense" belief in absolute space, and in an independent absolute time, might be no more than a local approximation, good enough for most purposes but unacceptable as a precise statement of the structure of the physical world. This, perhaps, we could swallow. But here is Bohr, suggesting that our notion of causality (and through similar argumentation our notions of the distinction between subject and object, and even of observation itself) may be only good enough for most human purposes, but, finally, only good enough for rough analyses:

⁶ Niels Bohr, *Atomic Theory...*, op. cit., p. 11.

⁷ Ibidem, p. 54.

⁸ Ibidem, p. 67.

Just as the relativity theory has taught us that the convenience of distinguishing sharply between space and time rests solely on the smallness of the velocities ordinarily met with compared to the velocity of light, we learn from the quantum theory that the appropriateness of our usual causal space-time description depends entirely upon the small value of the quantum of action as compared to the actions involved in ordinary sense perceptions⁹.

The conclusions that we may draw from this are by now of obvious philosophical moment, I should hope. If Bohr is right, then we have learned that, finally, there is no objective way to distinguish between subject and object, between observer and observed, between thinker and world. This is itself an objective truth about the world, if Bohr is right. We can say, with precision enough, that such-and-such a way of making the distinction – of defining the world, of characterizing it – might be perfectly acceptable for so-and-so purposes, but none is canonical. None is best for all purposes. This is a relativistic metaphysic, but it shares with all relativisms a curiously objectivist motivation. In seeking to say something that holds absolutely, with no exceptions, we find that the only plausible things that we can say are relativistic.

The epistemology that falls out of all this has just the characteristics that one would anticipate. First of all, it has a great deal to say about description and about the theories we build up about the world around us. It suggests that a particular description of the phenomena may be more or less expedient, that the reality of this thing or that thing is to be determined by the usefulness of positing such reality¹⁰. Indeed, Bohr was the first to point out that

(...) in consequence of this state of affairs, even worlds like 'to be' and 'to know' lose their unambiguous meaning¹¹.

It is not so much that we can't get in touch with the "real" world; it is that we are too much in touch with it. We cannot, fi-

⁹ Ibidem, p. 55.0

¹⁰ Ibidem, p. 12.

¹¹ Ibidem, p. 19.

nally, shove it away far enough to look at without interfering with it. The world we look at is what is in large part because of our looking at it. We can stipulate that it is unaffected by our inquiry, and this might be a perfectly wise thing to do for one purpose or another. But it can never be literally true that the world we observe is unaffected by our efforts to understand it. We change it; we even make it.

This, finally, is Bohr's epistemological legacy. To the extent that any of us, whether philosopher or physicist, chronicler or social scientist, hopes to describe the world, or to understand it, we must face one objective fact that may make, in the spirit of the principle of complementarity, all other facts more difficult to ascertain: our very attempt to describe or come to understand the world is an event in the world. It may not be something that can be neglected. But one thing is certain: a fully accurate description of the world cannot neglect it. The patent truth, the obvious truth, is that the world is peopled with observers, whose efforts to describe and understand that world make up a large part of what they are trying to describe and understand. Bohr, with his colleagues, uncovered, from the perspective of physics, the limits of description itself.