RECONSIDERING BOHR'S REPLY TO EPR

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Abstract. Although Bohr's reply to the EPR argument is supposed to be a watershed moment in the development of his philosophy of quantum theory, it is difficult to find a clear statement of the reply's philosophical point. Moreover, some have claimed that the point is simply that Bohr is a radical positivist. In this paper, we show that such claims are unfounded. In particular, we give a mathematically rigorous reconstruction of Bohr's reply to the *original* EPR argument that clarifies its logical structure, and which shows that it does not rest on questionable philosophical assumptions. Rather, Bohr's reply is dictated by his commitment to provide "classical" and "objective" descriptions of experimental phenomena.

1. Introduction

The past few decades have seen tremendous growth in our understanding of interpretations of quantum mechanics. For example, a number of "no-go" results have been obtained which show that some or other interpretation violates constraints that we would expect any plausible interpretation of quantum mechanics to satisfy. Thus, although there is no immediate hope of convergence of opinion on interpretive issues, we certainly have an increased understanding of the technical and conceptual issues at stake. Perhaps, then, we can make use of this increased technical awareness to shed some new light on the great old episodes in the conceptual development of quantum mechanics.

One historical episode of enduring philosophical interest is the debate between Bohr and Einstein (along with Podolsky and Rosen) over the completeness of quantum mechanics. Although folklore has it that Bohr was the victor in this debate, Fine and Beller [15] have recently claimed that Bohr's reply to the EPR argument of 1935 is basically a failure. In particular, Fine and Beller claim that "[...] as a result of EPR, Bohr eventually turned from his original concept of disturbance, to make a final—and somewhat forced—landing in positivism" [15, p. 29]. They also make the stronger philosophical claim that "[...] a positivistic shift is the only salvageable version of Bohr's reply" [15, p. 9]. Unfortunately, Fine and Beller do not devote much attention to establishing this philosophical claim. (Nor does it seem to us that Beller's more extended treatment [2, Chap. 7] goes any further towards establishing the philosophical claim.) Even if we concede—for purposes of argument—that the later Bohr embraced positivism, we are *not*

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willing to concede that he was rationally compelled to do so. In fact, we will argue that Bohr's defense of the completeness of quantum mechanics does not depend in any way on questionable philosophical doctrines. To this end, we will supply a formal reconstruction of Bohr's reply to EPR, showing that his reply is dictated by the dual requirements that any description of experimental data must be *classical* and *objective*.

The structure of this paper is as follows. In Section 2, we provide an informal preliminary account of the EPR argument and of Bohr's reply. In Section 3, we consider some salient features of Bohr's general outlook on quantum theory. We then return to Bohr's reply to EPR in Sections 4 and 5. In Section 4, we reconstruct Bohr's reply to EPR in the case of Bohm's simplified spin version of the EPR experiment. Finally, in Section 5, we reconstruct Bohr's reply to EPR in the case of the original (position-momentum) version of the EPR experiment.

2. Informal preview

In classical mechanics, a state description for a point particle includes a precise specification of both its position and its momentum. In contrast, a quantum-mechanical state description supplies only a statistical distribution over various position and momentum values. It would be quite natural, then, to regard the quantum-mechanical description as *incomplete*—i.e. as providing less than the full amount of information about the particle. Bohr, however, insists that the imprecision in the quantum-mechanical state description reflects a fundamental indeterminacy in nature rather than the incompleteness of the theory. The EPR argument attempts to directly rebut this completeness claim by showing that quantum mechanics (in conjunction with plausible extra-theoretical constraints) entails that particles always have both a precise position and a precise momentum.

EPR ask us to consider a system consisting of a pair of spacelike separated particles. They then note that, according to quantum mechanics, there is a state ψ_{epr} in which the positions of the two particles are strictly correlated, *and* the momenta of the two particles are strictly correlated. It follows then that if we were to measure the position of the first particle, we could predict with certainty the outcome of a position measurement on the second particle; *and* if we were to measure the momentum of the first particle, we could predict with certainty the outcome of a momentum measurement on the second particle.

EPR then claim that our ability to predict with certainty the outcomes of these measurements on the second particle shows that each such measurement reveals a pre-existing "element of reality." In what has come to be know as the "EPR reality criterion", they say:

> If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity. [13, p. 77]

In particular, if we determine the position of the first particle in this strictly correlated state, then we can conclude that the second particle also has a definite position. And if we determine the momentum of the first particle in this strictly correlated state, then the second particle must also have a definite momentum.

Of course, it does not immediately follow that there is any single situation in which both the position and the momentum of the second particle are elements of reality. However, EPR also make the (*prima facie* plausible) assumption that what counts as an element of reality for the second particle should be independent of which measurement is performed on the first particle. In other words, a measurement on the first particle can play a *probative*, but not a *constitutive*, role with respect to the elements of reality for the second particle. Consequently, EPR conclude that both the position and the momentum of the second particle are elements of reality, regardless of which measurement is performed on the first particle.

2.1. BOHR'S REPLY

According to Bohr, the EPR argument somehow misses the point about the nature of quantum-mechanical description. Unfortunately, though, not much scholarly work has been done attempting to reconstruct Bohr's reply in a cogent fashion.

We should begin by noting that Bohr most certainly does not maintain the "hyperpositivist" position according to which no possessed properties or reality should be attributed to an unmeasured system. (For example, Ruark claims that, for Bohr, "a given system has reality only when it is actually measured" [25, p. 466].) Quite to the contrary, Bohr explicitly claims that when the position of the first particle is measured, "[...] we obtain a basis for conclusions about the initial position of the other particle relative to the rest of the apparatus" [3, p. 148]. Thus, Bohr agrees with EPR that once the position (respectively, momentum) of the first particle is actually measured, the position of the second particle is an element of reality—*whether or not* its position is actually empirically determined. In other words, Bohr accepts the outcome of an application of the EPR reality criterion, so long as its application is restricted to individual measurement contexts (i.e. the results of its application in different contexts are not combined).

In order, then, to rationally reject EPR's conclusion, Bohr must reject the claim that elements of reality for the second particle cannot be constituted by measurements carried out on the first particle. In other words, Bohr believes that a measurement on the first particle *can* serve to constitute elements of reality for the second, spacelike separated, particle.

To this point, we have not said anything particularly novel about Bohr's reply to EPR. It is relatively well-known that his reply amounts to claiming—what EPR thought was absurd [13, p. 480]—that what is real with respect to the second particle can depend in a nontrivial way on which measurement is performed on the first particle. However, where previous defenders of Bohr have uniformly stumbled is in giving a coherent account of *how* a measurement on one system can influence what is real for some spacelike separated system.

Unfortunately, Bohr's statements on this issue are brief and obscure. For example, he says,

> It is true that in the measurements under consideration any direct mechanical interaction of the [second] system and the measuring agencies is excluded, but a closer examination reveals that the procedure of measurement has an essential influence on the conditions on which the very definition of the physical quantities in question rests. [4, p. 65]

That is, a measurement on the first system influences the conditions which must obtain in order for us to "define" elements of reality for the second system. Moreover, this influence is of such a sort that a position (momentum) measurement on the first particle supplies the conditions needed to define the position (momentum) of the second particle.

Before we proceed to our positive account, we need first to dismiss one *prima facie* plausible, but nonetheless mistaken, explication of Bohr's notion of defining a quantity. In particular, some have claimed that, according to Bohr, an observable of a system comes to have a definite value when the wavefunction of the system collapses onto one of that observable's eigenstates. This amounts to attributing to Bohr the claim that:

Eigenstate-Eigenvalue Link: A quantity Q is defined in state ψ iff ψ is an eigenvector for Q;

along with the claim that by measuring an observable, we can cause the quantum state to collapse onto an eigenstate of that observable. In that case, Bohr would claim that by measuring the position of the first particle, we collapse the EPR state onto an eigenstate of position for the second particle—and thereby "cause" the second particle to have a definite position. Similarly, if we were to measure the momentum of the first particle, we would "cause" the second particle to have a definite momentum. In either case, the measurement on the first particle would be the cause of the reality associated with the second particle.

However, there are at least two good reasons for rejecting this reading of Bohr. First, Bohr explicitly claims that a measurement of the first particle cannot bring about a "mechanical" change in the second particle. In philosophical terms, we might say that Bohr does not believe that the position measurement on the first particle *causes* the second particle to have a position, at least not in the same sense that a brick can *cause* a window to shatter. Thus, if Bohr does believe in a collapse the wavefunction, it is as some sort of *non-physical* (perhaps epistemic) process. However, it is our firm opinion that, unless the quantum state can be taken to represent our ignorance of the "true" hidden state of the system, there is no coherent non-physical interpretation of collapse. (We doubt the coherence of recent attempts to maintain both a subjectivist interpretation of quantum probabilities, and the claim that "there are no unknown quantum states" [9].) Thus, if Bohr endorses collapse, then he is already committed to the incompleteness of quantum mechanics, and the EPR argument is superfluous.

The second, and more important, reason for resisting this reading of Bohr is the complete lack of textual evidence supporting the claim that Bohr believed in wavefunction collapse (see [20]). Thus, there is no good reason to think that Bohr's reply to the EPR argument depends in any way on the notion of wavefunction collapse.

3. Classical description and appropriate mixtures

In order to do justice to Bohr's reply to EPR, it is essential that we avoid caricatured views of Bohr's general philosophical outlook, and of his interpretation of quantum mechanics. This is particularly difficult, because there has been a long history of misinterpretation of Bohr. For example, in terms of general philosophical themes, one might find Bohr associated with anti-realism, idealism, and subjectivism. Moreover, in terms of the specific features of an interpretation of quantum mechanics, Bohr is often associated with wavefunction collapse, creation of properties/attributes upon measurement, and "cuts" between the microscopic and macroscopic realms. However, these characterizations of Bohr are pure distortion, and can find no justification in his published work. Indeed, Bohr's philosophical commitments, and the picture of quantum mechanics that arises from these commitments, are radically different from the mythical version that we have received from his critics and from his well-intended (but mistaken) followers. (Our own understanding of Bohr has its most immediate precedent in recent work on "no collapse" interpretations of quantum mechanics [6, 7, 8, 17]. However, this sort of analysis of Bohr's interpretation was suggested independently, and much earlier, by Don Howard [18]. See also [19, 20].)

According to Bohr, the phenomena investigated by quantum theory cannot be accounted for within the confines of classical physics. Nonetheless, he claims that "[...] however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms" [5, p. 209]. That is, classical physics embodies a standard of intelligibility that should be exemplified by any description of the empirical evidence. In particular, although the various sources of evidence cannot be reconciled into a single classical picture, the description of any single source of evidence must be classical.

Bohr's statements about the notion of "classical description" have been horribly misunderstood. For a catalog of these misunderstandings and for evidence that they are indeed mistaken, we refer the reader to [18, 19, 20]. On the positive side, we will follow Howard [19] in the claim that the notion of classical description is best explicated via the notion of an "appropriate mixture."

> [...] we make the clearest sense out of Bohr's stress on the importance of a classical account of experimental arrangements and of the results of observation, if we understand a classical description to be one in terms of appropriate mixtures. [19, p. 222]

As Howard [18] shows, the notion of an appropriate mixture can be developed in such a way that Bohr's (sometimes obscure) statements about the possibilities of classical description become mathematically clear statements about the possibility of treating the quantum state as a classical probability measure. In order to see this, we first collect some terminology.

Let $\mathcal{H}$ be a finite-dimensional vector space with inner-product $\langle\cdot,\cdot\rangle$, and let $\mathbf{B}(\mathcal{H})$ denote the family of linear operators on $\mathcal{H}$. We say that a self-adjoint operator W on $\mathcal{H}$ is a *density operator* just in case W has non-negative eigenvalues that sum to 1. If ψ is a vector in $\mathcal{H}$, we let $|\psi\rangle\langle\psi|$ denote the projection onto the ray in $\mathcal{H}$ generated by ψ. Thus, if Tr denotes the trace on $\mathbf{B}(\mathcal{H})$, then $\mathrm{Tr}(|\psi\rangle\langle\psi|A) = \langle\psi, A\psi\rangle$ for any operator A on $\mathcal{H}$. A *measurement context* can be represented by a pair (ψ, R), where ψ is a unit vector (representing the quantum state), and R is a self-adjoint operator (representing the measured observable).

Following Howard [18], we say that a "mixture," represented by a density operator W, is *appropriate* for (ψ, R) just in case $W = \sum_{i=1}^{n} \lambda_i |\phi_i\rangle\langle\phi_i|$, $(n \leqslant \dim\mathcal{H})$, where each ϕ_i is an eigenvector for R, and $\lambda_i = |\langle\psi,\phi_i\rangle|^2$ for $i = 1,\ldots,n$. In other words, W is a mixture of eigenstates for R, and it reproduces the probability distribution that ψ assigns to the values of R. Thus, an appropriate mixture for (ψ, R) can be taken to represent our ignorance of the value of R in the state ψ.

Once again, we emphasize that Bohr never explicitly invokes wavefunction collapse, nor does he need to. Indeed, the idea of a "measurement problem" was foreign to Bohr,

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