An Everett Perspective on Bohr and EPR

Guido Bacciagaluppi*

29 February 2016

Abstract

After summarising a previously given analysis of Bohr's reply to Einstein, Podolsky and Rosen (EPR), this chapter endorses the claim made by Everett himself that Everettian quantum mechanics 'in a certain sense bridges the positions of Einstein and Bohr'. On the one hand, it shows how Everett's theory provides a reconstruction of Bohr's viewpoint of complementarity as applied to the EPR case and a justification of his criticism of EPR's 'criterion of reality'. On the other hand, it includes a notion of physical reality that is independent of any observational context, and suggests a remaining shortcoming of Bohr's reply.

Keywords: Bohr and EPR, Everett, complementarity

1 Introduction

One of the most noteworthy developments in the philosophy of quantum mechanics since the early 1990s – closely related to the rise of structuralist positions in philosophy of science – has been the renaissance of the Everett theory (for the state of

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*Descartes Centre for the History and Philosophy of the Sciences and the Humanities, Utrecht University, Utrecht, The Netherlands; IHPST (CNRS, ENS, Paris 1) and SPHERE (CNRS, Paris 7, Paris 1), Paris, France; FQXi – Foundational Questions Institute, http://fqxi.org/ ; email: g.bacciagaluppi@uu.nl .

the art, see e.g. Saunders *et al.* (2010) and Wallace (2012)). Ignored in the 1950s and 1960s, notorious in the 1970s and 1980s for the outlandish claims of some of its more 'popular' versions, for a long time it was deeply suspect to most philosophers of physics, appearing as it did as measurement-induced collapse with the added grief of all the unwanted components. The philosophical landscape changed dramatically in the 1990s and 2000s with the work of Simon Saunders, David Wallace and others, who reconceptualised the Everett theory along structuralist-functionalist lines and assigned a central role to decoherence theory (vindicating in hindsight ideas developed by Hans-Dieter Zeh in the 1970s). With the decision-theoretic approach by Deutsch and by Wallace and the work on confirmation by Greaves and others providing further a serious candidate for the meaning of probabilities in the theory, the Everett theory at last gained the status of a well worked-out approach to the foundations of quantum mechanics, alongside the more familiar de Broglie-Bohm and spontaneous collapse theories, and seen by many even as the approach of choice, for its lack of theoretical revisionism and the relatively effortless compatibility with relativity (on which more below).

Even more recently, historians and historically oriented philosophers of quantum mechanics have provided an analogous re-evaluation of the figure and work of Everett himself (Byrne 2010, Everett 2012, Freire 2015). As I have had the opportunity to stress elsewhere (Bacciagaluppi 2013), Everett's own work is far richer than the reductive image philosophers of physics have inherited of it from the pre-1990s period, and far closer to our current understanding (even though it does not use the technical tools of decoherence) – even in some aspects of its approach to probabilities. One point that has emerged from this historical work and is particularly significant to this chapter, is the rather tragic interplay between Everett and his theory and Bohr and his circle and the Copenhagen interpretation (see in particular Osnaghi *et al.* 2009). We now know that Wheeler would not let Everett's thesis pass until it was stripped of any elements that might fail to get Bohr's blessing – which was repeatedly sought and refused – a train of events that ultimately contributed to Everett's abandonment of physics. Everett, for his part, while aiming to leave behind Bohr's 'overcautious' stance, was perfectly satisfied that complementarity was in fact subsumed in his theory (see e.g. Everett 2012, pp. 18, 153 and 175).

In recent work with Elise Crull (Bacciagaluppi and Crull 2016), I have been re-examining Bohr's reply to the EPR paper (which is a central source for Bohr's ideas on complementarity), trying to clarify in particular Bohr's distinction between 'mechanical disturbance' and other kinds of 'influence' in his strategy of criticising EPR's 'criterion of reality'. A helpful framework for our analysis is provided by Howard's

(1994) discussion of Bohr's doctrine of classical concepts, originally published in the predecessor to this volume. On the other hand, as argued in particular by Beller and Fine (1994) also in the predecessor to this volume, Bohr's approach to the 'problem of physical reality' appears to drive him towards a positivist position. In this chapter, after briefly summarising the essentials of EPR and in somewhat more detail our previous analysis of Bohr's reply, I shall suggest that Everett's theory indeed succeeds in recapturing Bohr's ideas about complementarity as expressed in the reply to EPR, but in a realist framework that goes some way toward mediating between Bohr and Einstein.[1] Such an Everettian perspective also suggests which aspects remain problematic in Bohr's reply to EPR.

2 EPR in a nutshell

As is well known,[2] the EPR argument was a development of Einstein's photon-box thought experiment of 1930: a clockwork mechanism opens a box at a precise time, letting exactly one photon out. We can thus know the exact time of emission of the photon. But we can also weigh the box before and after emission, and using mass-energy equivalence we can thus measure also the energy of the photon. In his later recollections, Bohr (1949) sees the photon-box experiment as an attempt to criticise the *empirical* validity of the uncertainty relations. At the latest a few months later, however, it is clear that Einstein was thinking of the experiment as a critique of the alleged *ontological* implications of the uncertainty relations (that the energy and time of emission of the photon cannot be simultaneously well-defined). In the terminology of EPR, the aim of the critique is not the correctness of quantum mechanics but its completeness, which was arguably Einstein's main concern all along. As Ehrenfest (in his inimitable style) explains in a letter to Bohr, Einstein did not doubt the validity of the uncertainty relations and had not devised the photon-box to that end, rather his actual interest in the thought experiment was that:[3]

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[1] This is a sentiment shared by Everett himself: 'Our theory in a certain sense bridges the positions of Einstein and Bohr, since the complete theory is quite objective and deterministic [...], and yet on the subjective level, of assertions relative to observer states, it is probabilistic in the *strong sense* that there is no way for observers to make any predictions better than the limitations imposed by the uncertainty principle' (Everett 2012, p. 158).

[2] For a classic summary, see Jammer (1974, Sects. 5.2, 6.2 and 6.3), and for necessary correctives Fine (1986, Chap. 3) and Howard (1990).

[3] Ehrenfest to Bohr, 9 July 1931, AHQP-EHR 17 (in German). All translations are by Elise Crull and/or myself.

> it is interesting to be clear about the fact that the projectile [the photon], which is already flying about in isolation “on its own”, must be ready to satisfy very different ““non-commutative”” [sic] prophecies, “without even knowing” which one of these prophecies one will make (and check).

The EPR paper published in May 1935 argues for the incompleteness of quantum mechanics by arguing for the existence of ‘elements of physical reality’ not included in the quantum mechanical description. To do this, EPR need a sufficient criterion for the existence of such elements of physical reality, namely (Einstein, Podolsky and Rosen 1935, p. 777, italics in the original):

> *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.*

EPR consider in particular two no longer interacting systems in a generic entangled state $\Psi(x_1, x_2)$, which they write in two alternative ways (their eqs. (7) and (8)):

$$\Psi(x_1, x_2) = \sum_{n=1}^{\infty} \psi_n(x_2) u_n(x_1) = \sum_{s=1}^{\infty} \varphi_s(x_2) v_s(x_1) \ , \tag{1}$$

or (I switch to Dirac notation for later convenience)

$$|\Psi\rangle = \sum_{n=1}^{\infty} |\psi_n\rangle |u_n\rangle = \sum_{s=1}^{\infty} |\varphi_s\rangle |v_s\rangle \ , \tag{2}$$

where the states $|u_n\rangle$ and $|v_s\rangle$ are, respectively, (normalised) eigenstates of quantities A and B on system I, and the states $|\psi_n\rangle$ and $|\varphi_s\rangle$ are (not necessarily normalised or orthogonal) states of system II. Depending on whether one chooses to measure A or B, system II is then left in a state corresponding to either a (non-zero) $|\psi_n\rangle$ or a (non-zero) $|\varphi_s\rangle$. They further note: ‘On the other hand, since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system’ (p. 779).

The reasoning is not spelled out in the paper, but even without invoking the criterion of reality it now follows immediately that neither of these wave functions can provide a complete description of the state of system II. At most they can be incomplete descriptions of the same real state of the system. Indeed, as pointed out by both Fine and Howard, this indirect reasoning was Einstein's preferred version of the argument, and he thought the main point had not come across clearly in the published paper.

In the paper, EPR then turn to a special case, in which they proceed to apply the criterion of reality to establish the existence of elements of reality. Their special case is given by the state

$$|\Psi\rangle = \int_{-\infty}^{\infty} e^{ix_0/\hbar} |-p\rangle |p\rangle \, dp = \int_{-\infty}^{\infty} |x + x_0\rangle |x\rangle \, dx \tag{3}$$

where $|p\rangle$ and $|x\rangle$ are the standard (improper) eigenkets of momentum and position: whenever the measurement of momentum on system I yields the outcome p, system II is left in the momentum eigenstate corresponding to the eigenvalue $-p$, and whenever the measurement of position on system I yields the outcome x, system II is left in the position eigenstate corresponding to the eigenvalue $x + x_0$.[4]

Judging by the different readings in the literature (see Whitaker (2004) for an overview), the form of EPR's reasoning is not entirely clear. The following, however, is a straightforward reading that fits very well also with Bohr's reply. The criterion of reality is a conditional, with a statement about possibility in the antecedent. The special example considered by EPR establishes this antecedent: it is indeed possible to measure position on system I apparently without disturbing system II in any way. Therefore, the consequent follows by *modus ponens*: there is an element of reality corresponding to system II's position. The same reasoning applied to momentum establishes that there is an element of reality corresponding also to system II's momentum. (Note that the reasoning nowhere requires such non-disturbing measurements to be actually carried out, only that it be possible to carry them out.) Since no quantum mechanical state includes values of both position and momentum in the description it gives of a system, the quantum mechanical description of reality is incomplete.

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[4] Note that such a state is not given by a Schrödinger wave function; indeed, it is even more singular than a Dirac delta function. For a rigorous treatment in the formalism of C^* algebras, see Halvorson (2000). Standard wave functions, however, suffice to describe approximate EPR states. The mathematical details will be inessential to our discussion of either the EPR argument or Bohr's reply.

3 Bohr's reply revisited

In his reply published in October 1935, Bohr addressed the argument as presented in the paper, and appears to read it as suggested above. His strategy is to undermine the criterion of reality as containing an 'essential ambiguity' when applied to this case, so that EPR's claim no longer follows. As Bohr explains, the ambiguity in the criterion of reality is that while there is no 'mechanical disturbance' of the second particle when the first one is measured (i.e. there is no interaction with the second particle), there is '*an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*' (Bohr 1935, p. 700, italics in the original). According to Bohr it is this kind of influence – not mere 'mechanical disturbance' – that EPR need to rule out to be able to apply the criterion.

Furthermore, such 'influence' is a very general feature of quantum measurements ('an essential property of any arrangement suited to the study of the phenomena of the type concerned', p. 697), already captured by his 'viewpoint termed "complementarity"', with the EPR example involving no 'greater intricacies'. And, indeed, what Bohr does is to discuss at length an example of a simple quantum measurement, a particle passing through a single slit in a diaphragm initially movable along a given direction, where the initial momentum along that direction of both the particle and the diaphragm are known. (Later in the paper Bohr models explicitly also the EPR state of two microscopic particles, but for the purpose of his argument, he has no need of it.) Passage through the slit narrows the uncertainty in the position of the particle, and an 'exchange of momentum' takes place between particle and diaphragm. Note that the total momentum and the difference in positions are then known, as in the EPR case. Note also that the original 'exchange of momentum' between particle and diaphragm is a 'mechanical' interaction, of course, but we are not interested in retrodicting the initial state of the particle (which Bohr explicitly says could be a known eigenstate of momentum), but in what predictions can be made about results of further measurements. Such predictions can now be made by manipulating only the diaphragm, so that there is no longer any interaction with the particle, again analogously to the EPR case. Note finally that (as mentioned by Bohr in his initial summary of the EPR argument) all of the above applies equally well if we describe the situation using classical mechanics.

The difference between the classical and quantum mechanical descriptions lies in the limitations arising from the choice of manipulations on the diaphragm. Specifically, if we wish to predict the position or the momentum of the particle by manipulating the diaphragm, we need to be able to reconstruct the relevant aspect of how the particle affected the diaphragm when they originally interacted. Bohr calls this 'controlling the reaction of the object on the measuring instruments if these are to serve their purpose' (p. 697). If we can legitimately use the 'idea of space location' in describing the diaphragm and its interaction with the particle, then by performing a position measurement on the diaphragm (immediately after the passage of the particle[5]), we can predict the result of a further position measurement on the particle; and if we can apply the 'conservation theorem of momentum' in describing the diaphragm and its interaction with the particle, then by performing a momentum measurement on the diaphragm we can predict the result of a further momentum measurement on the particle.

Crucially now the different choices of how to complete the measurement preclude the applicability of one or other of these classical ideas (rendering 'maximal' the set of measurements whose results are predictable with certainty). If we measure the position of the diaphragm, its momentum becomes completely uncertain, and we may no longer legitimately apply the conservation theorem. Thus we have 'voluntarily cut ourselves off' from the possibility of reconstructing the exchange of momentum between particle and diaphragm. If we determine the momentum of the diaphragm, its position becomes completely uncertain, and we may no longer apply the idea of spatial location. Thus we have 'voluntarily cut ourselves off' from the possibility of reconstructing the space-time coordination of particle and diaphragm.

This analysis of measurement applies equally well to Bohr's example as to the EPR example, as emphasised also by Pauli in a letter of 9 July 1935 in which he describes to Schrödinger the strategy of Bohr's reply (Pauli 1985, p. 420):

> A pure case of A is an overall situation in which the results of particular measurements on A (a maximal set) are predictable with certainty. I have nothing against calling this the 'state' – but even then it *is* the case that changing the state of A – i.e. that which is predictable of A – lies within the *free choice* of the experimenter even without directly disturbing A itself – i.e. even *after* isolating A. [...] In my opinion *there is in fact no problem here* – and one knows the fact in question even without the

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[5] This is somewhat a limitation of Bohr's example, but note that also in the EPR paper there are no considerations of dynamics: depending on how the EPR state evolves, the observable whose values we can predict with certainty on system II, and the measurement we need to perform on system I, will not necessarily be position and will depend on the time of the further measurement (as discussed by Schrödinger (1935, Sect. 4)).

Einstein example.

For instance, as Jammer (1974, pp. 96–97) points out, Bohr's example is almost identical to another famous thought experiment, Heisenberg's γ-ray microscope. Indeed, in both cases one has two systems immediately after the interaction in a state of known total momentum and zero difference in position (or approximately so: in Bohr's case because of the finite width of the slit, in Heisenberg's case because of the finite size of the microscope). In the case of the microscope, the freedom of choice in completing the measurement had been explicitly discussed by Weizsäcker (1931), and put to crucial use both by Grete Hermann (1935) as the lynchpin of her analysis of causality and complementarity in quantum mechanics, and by Heisenberg in his own draft reply to EPR from the summer of 1935 (instigated by Pauli and related to Hermann's analysis).[6] Note that while neither thought experiment is a fully generic example of quantum measurement, because the state after the interaction is maximally entangled (or approximately so), the main point remains the same even if the entanglement between system and measuring instrument, or any other auxiliary system (in modern parlance an 'ancilla'), is not maximal: choosing to perform one or another of alternative projective measurements on the auxiliary system still results in different kinds of states of the system, just as in EPR's more general example (2).

Let us take stock. As far as Bohr's quantum mechanical description of the particle and diaphragm goes, nothing is in dispute here. EPR accept the correctness of quantum mechanics, and, indeed, the idea that the choice of measurements performed on one system determines which quantum state we assign to another system is explicitly asserted in the EPR paper. Even the idea of some kind of 'cutting oneself off' need not be an issue. For instance, if quantum mechanics is correct, it is not in dispute that when we determine the position of the diaphragm its momentum will become totally uncertain, in the empirical sense of becoming unpredictable. But even if in this empirical sense 'cutting oneself off' should be utterly final and irreversible, all that Bohr has established so far is compatible with the idea that by choosing to perform, say, a measurement of position on the diaphragm, we cut ourselves off merely *epistemically* from gaining access to the momentum of the particle. The only advance on a naïve disturbance theory of measurement would be that instead of saying

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[6] Hermann's essay (published in March 1935) argues that quantum mechanics is causally complete, but that causal chains can be only reconstructed in retrospect, thus severing the classical link between causality and prediction. It then goes on to provide a comprehensive analysis of complementarity from a neo-Kantian perspective. For a full translation, see Crull and Bacciagaluppi (2016). For Heisenberg's reply to EPR and its relation to Hermann's essay, see Bacciagaluppi and Crull (2009, 2016) and Crull and Bacciagaluppi (2011, 2016).

that measuring the position of the particle uncontrollably disturbs the momentum of the particle (thus conceding that it exists), we say that measuring the position of the particle uncontrollably disturbs our possibility of knowing the momentum of the particle (thus equally conceding it exists). Bohr, however, emphasises that 'cutting oneself off' is not meant merely epistemically: he states explicitly (p. 699) that

> we have in each experimental arrangement suited for the study of proper quantum phenomena not merely to do with an ignorance of the value of certain physical quantities, but with the impossibility of defining these quantities in an unambiguous way.

Bohr's position can be arguably spelled out in more detail using Howard's analysis of Bohr's doctrine of classical concepts. Howard (1994) has suggested that Bohr in fact agrees with Einstein on the fundamental necessity of the separability of system and apparatus for an objective description of the system (and the apparatus), but that he sees the 'finite interaction between object and measuring agencies conditioned by the very existence of the quantum of action' as genuinely destroying the possibility of such an objective description.[7] While separability can be regained within an observational context, the price to pay is that the resulting description crucially depends on the choice of the observational context, whereby different choices generally exclude each other. In this sense, what can be considered objective in each context is different, so that we have different descriptions that are objective but complementary to each other.

As a formal 'reconstruction' (a carefully chosen word) of Bohr's intuitions, Howard suggests we represent the lack of separability in terms of entanglement, and the passage to an observational context as substituting for the entangled state an appropriate mixture. Specifically, in the EPR case:

- we can choose to apply to both systems the idea of spatial location by substituting the mixture

  $$\int_{\infty}^{\infty} |x+x_0\rangle\langle x+x_0| \otimes |x\rangle\langle x| \, dx \ , \tag{4}$$

  which allows us to selectively exploit the position correlations in the EPR state;

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[7] As Bohr (1928) wrote in the Como lecture: 'the quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation'.

- or we can choose to apply to both systems the conservation of momentum by substituting the mixture

  $$\int_{\infty}^{\infty} |-p\rangle\langle -p| \otimes |p\rangle\langle p| \, dp \ , \tag{5}$$

  which allows us to selectively exploit the momentum correlations in the EPR state.

Unlike what one might have expected, in choosing an observational context Bohr does not treat the apparatus as classical and the system as quantum mechanical, but treats certain aspects of *both* system and apparatus as classical, at the expense of others. Note this is perfectly in line with our above remarks about the need to reconstruct certain aspects of the interaction between system and apparatus in order to make certain kinds of predictions about the system.

In this light, the core of the disagreement between Bohr and Einstein is the idea that quantum mechanical entanglement genuinely represents a lack of separability at the level of physical reality, as opposed to a failure to capture in the quantum mechanical description the underlying separability at the level of physical reality. The question remains why Bohr insists on the former, but in the next and final section we shall abandon this line of enquiry. We shall switch our focus to the Everett theory, endorsing the claim that Everett's theory can provide a detailed reconstruction of Bohr's views on complementarity, and indeed a justification of his specific criticism of the criterion of reality. The Everettian perspective, however, also includes a notion of physical reality that is independent of any observational context, and will suggest a different criticism of Bohr's reply.

4 Everett: the best of both worlds?

Everett takes seriously the idea of a wave function of the universe that evolves according to the usual Schrödinger equation. From the universal wave function (or indeed the wave function of any given system), which we shall write in Dirac notation as $|\Psi\rangle$, we can define two types of states for any subsystem. Marginal distributions and expectations for a subsystem II are given by the reduced *density matrix* $\mathrm{Tr}_{\mathrm{I}}(|\Psi\rangle\langle\Psi|)$ of the system (the density matrix obtained by taking the partial trace over the remaining degrees of freedom, comprising system I). Instead, a *relative state* $\langle\psi|\Psi\rangle$

gives the conditional distributions and expectations for subsystem II, conditional on any state $|\psi\rangle$ of system I for which $\langle\psi|\Psi\rangle \neq 0$ (Everett 2012, pp. 97–103).

In the example (2) above, the reduced density matrix of system II can be written in the alternative ways

$$\mathrm{Tr}_{\mathrm{I}}(|\Psi\rangle\langle\Psi|) = \sum_{n=1}^{\infty} |\psi_n\rangle\langle\psi_n| = \sum_{s=1}^{\infty} |\varphi_s\rangle\langle\varphi_s| \ , \tag{6}$$

or in fact infinitely many other ways. Each $|\psi_n\rangle$ is the state of II relative to $|u_n\rangle$ and each $|\varphi_s\rangle$ is the state of II relative to $|v_s\rangle$. However, there are infinitely many other ways of defining relative states for any given system. The usefulness of the concept is thus not immediately obvious. Everett's strategy for recovering standard quantum mechanics, however, is to consider systems ('servomechanisms') that have a complex enough structure that they can store (and maybe act upon) records of the relative states of other systems they have interacted with in certain (measurement-like) ways. The theory will recover standard quantum mechanics if it predicts the usual quantum statistics for 'typical' memory sequences of these observer systems (where it is clear that Everett has in mind an analogy with classical statistical mechanics).[8]

The consensus among today's Everettians is that the tool for identifying stable structures within the universal wave function is the theory of decoherence, and the strategy to recover the quantum probabilities is by suitably generalising Savage's representation theorem from classical decision theory.[9] Irrespectively of these details, when applied to measurement situations as the ones above, when the observer performs, say, a position measurement on the diaphragm, then relative to the observation of a particular value, the diaphragm and the particle will be in a relative state which is a product of the corresponding position states.[10] The relative state of the observer indeed records the corresponding state of the diaphragm and the

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[8] For Everett's discussion of observer memories see especially Everett (2012, pp. 118–119 and 137), and for his ideas on typicality see Everett (2012, pp. 123–130, 190–192, 261–264 and 294–295).

[9] See again Saunders *et al.* (2010, Parts 1 and 3) and Wallace (2012, Chaps. 3 and 5). Note that Everett's servomechanisms return as 'Information Gathering and Utilising Systems' (IGUSes) in discussions of decoherence, and that the mathematical core of the quantum representation theorem is related to that of Everett's own derivation of the Born rule.

[10] Similarly, relative to a position state of the particle, the apparatus and observer will be in a corresponding product state of position and recording position; and relative to a position state of the diaphragm, the particle and observer will be in a corresponding product state of position and recording position. Note again that the EPR state itself is highly singular, but if one considers suitably approximate states and realistic measurements, all relative states will be well defined.

particle, and this record is dynamically stable (insofar as guaranteed by continued decoherence interactions with the environment). At the same time, more than one record is present. This can be phrased in the language of worlds branching and/or observers splitting. More than one ‘copy’ of me is present, each recording a different result and dynamically decoupled from the others. When I look at the result, I realise which world I am in, and what from an absolute perspective is a deterministic development of different decoupled components within the universal wave function, appears from the relative perspective of my own state as an indeterministic process with associated collapse of the state of the system.

I now claim that the relative states of Everett’s theory are perfectly suitable to describe not only the empirical phenomena of quantum mechanics, as just sketched, but also the way these phenomena are seen from Bohr’s viewpoint of complementarity (at least as analysed above).

Consider first of all the state of the universe (or of that part that interests us) after the particle and diaphragm have interacted, but before we have chosen to measure either the position or the momentum of the diaphragm. This state is

$$|\Psi\rangle = \int_{-\infty}^{\infty} e^{ip_0/\hbar}|x\rangle|x\rangle\, dx = \int_{-\infty}^{\infty} |p_0 - p\rangle|p\rangle\, dp \tag{7}$$

(a state like (3) but with $x_0 = 0$ and some total momentum p_0), times a ‘ready’ state $|R\rangle$ of our measuring device (and/or of ourselves). Relative to the state $|R\rangle$, the particle and diaphragm are in the maximally entangled state (7), and neither has a (pure) relative state of its own.

Consider next the two possible choices of measuring the position or the momentum of the diaphragm. Depending on our choice, the total state either evolves to one including records $|R_x\rangle$ of the position of the diaphragm or to one including records $|R_p\rangle$ of its momentum, i.e. we have either

$$|\Psi\rangle|R\rangle = \int_{-\infty}^{\infty} e^{ip_0/\hbar}|x\rangle|x\rangle|R\rangle\, dx \;\mapsto \int_{-\infty}^{\infty} e^{ip_0/\hbar}|x\rangle|x\rangle|R_x\rangle\, dx \tag{8}$$

or

$$|\Psi\rangle|R\rangle = \int_{-\infty}^{\infty} |p_0 - p\rangle|p\rangle|R\rangle\, dp \;\mapsto \int_{-\infty}^{\infty} |p_0 - p\rangle|p\rangle|R_p\rangle\, dp\ . \tag{9}$$

In the first case, relative to a state $|R_x\rangle$ of the recording device, the particle and diaphragm are in the relative state $|x\rangle|x\rangle$. In the second case, relative to a state

$|R_p\rangle$ of the recording device, the particle and diaphragm are in the relative state $|p_0 - p\rangle|p\rangle$.

Note that under the evolutions in (8) and (9), respectively, the density matrix of the composite of particle and diaphragm evolves from $|\Psi\rangle\langle\Psi|$ to either

$$\int_{\infty}^{\infty} |x\rangle\langle x| \otimes |x\rangle\langle x|\, dx \tag{10}$$

or

$$\int_{\infty}^{\infty} |p_0 - p\rangle\langle p_0 - p| \otimes |p\rangle\langle p|\, dp\ , \tag{11}$$

i.e. the appropriate mixtures (4) or (5) of Howard's analysis. Before we have looked at the measurement result, these mixtures have an ignorance interpretation for us (and in this sense they are classical mixtures): 'we' (the relevant copy or ourselves) live in only one branch of the universal wave function, in which the state of the particle is either one particular $|x\rangle\langle x|$ or one particular $|p_0 - p\rangle\langle p_0 - p|$. And this disjunction is exclusive in a strong sense: if we ourselves had not yet interacted in any way (even without consciously observing the result) with the recording device, we could still undo its interaction with the diaphragm at least in principle ('quantum erasure') and change our mind between choice (10) or (11), but as soon as we do interact with the recording device, we split into different copies of ourselves, and as far as what is in our power, we have indeed irreversibly 'cut ourselves off' from the possibility of measuring the other quantity instead. In principle (and with a nod to Wigner), some friend of ours who had not yet interacted with us could undo the interaction. In practice, however, as soon as a macroscopic diaphragm or measuring device are involved, decoherence kicks in, and the universal wave function branches in an effectively irreversible way into worlds containing positions and records of position or momenta and records of momenta.

Crucially, moreover, we can now see that cutting oneself off is not merely epistemic, in the following sense. Indeed, even though the original state $|\Psi\rangle$ can be written non-uniquely in the biorthogonal forms (7), i.e. at this stage we can still choose to exploit either the correlations in position or the correlations in momentum, the triorthogonal decompositions in (8) and (9) are unique (Elby and Bub 1994). In the first case, there are no states of the recording device other than $|R_x\rangle$ for which the relative states of particle and diaphragm have product form (i.e. for any other states of the recording device, the relative state of the composite particle and diaphragm is entangled, and neither the particle nor the diaphragm have a relative state of their own); and similarly in the second case there are no states of the recording device other than $|R_p\rangle$ for which the relative states of particle and diaphragm have product form. Thus, when we choose to measure, say, the position of the diaphragm, we gain access to one of the components $|x\rangle\langle x|$ of (10). But now, while the other position components are contained in the other worlds that have branched away from ours when we performed the measurement, there are no worlds containing any momentum components! In this sense, cutting oneself off from the momentum of the particle is to be understood in an ontic rather than an epistemic sense: there is nothing to be known by us or any of our counterparts about the momentum of the particle in our or, indeed, any other world.

Thus the Everett theory is able to rederive Bohr's critique of EPR's criterion of reality: the 'physical reality' one can be ignorant about in a world does in fact depend on the choice of manipulation made by the observer without 'mechanically' disturbing the system of interest, so that the EPR criterion of reality is not applicable to the EPR example. That is not the end of the story, however.

Indeed, the Everett theory does not only contain 'physical reality' as relativised to an observational context and as represented by the relative states, but also an absolute notion of 'physical reality' that remains undisturbed by 'mechanical' interactions and that is represented by the reduced density matrices. In Bohr's example, irrespective of whether we choose to measure position or momentum on the diaphragm, the density matrix of the particle is and remains the maximally mixed state

$$\int_{-\infty}^{\infty} |x\rangle\langle x|\, dx = \int_{-\infty}^{\infty} |p_0 - p\rangle\langle p_0 - p|\, dp \tag{12}$$

(an improper mixture, because in the Everett theory there is no collapse), and in this sense the position components $|x\rangle\langle x|$ and the momentum components $|p_0 - p\rangle\langle p_0 - p|$ are still there, in fact all of them, even when we choose to perform the other measurement. Thus, the quantum mechanical description of reality as given by a particular position or momentum state after the corresponding measurement is clearly incomplete. It is true that the resulting incompleteness does not support Einstein's conclusion that the quantum state is merely a statistical description, but the fact that the absolute state of the particle is and remains (12) is still important in the context of Bohr's reply to EPR, for the following reason.

Suppose Bob (Bohr) has performed a position measurement on the diaphragm. In so doing, he has gained access to some particular component $|x\rangle$ of the state of the particle. The other position components are in different worlds, and the momentum components would even require reinterference between the different worlds in order to be reconstituted. The state $|x\rangle$ that he assigns to the particle is the one that he needs to use in order to make any further predictions of the future behaviour of the particle, because it is the only component of its absolute state he is able to interact with if he goes on to make measurements on the particle (which of course in general requires entangling it with some new instrument or ancilla). If he performs a position measurement, he will indeed find that the particle is in the state $|x\rangle$, thereby confirming the continued applicability of the 'idea of space location' he has used to attribute the state to the particle in the first place.[11] And if he performs a subsequent momentum measurement on the particle, the state $|x\rangle$ will split into its (own) momentum components, independently of whatever result he might have obtained had he originally performed a momentum measurement on the diaphragm. Thus, the Everett theory helps us see how the viewpoint of complementarity can indeed explain the results of any other measurements that Bob might perform.

But let us now switch to the actual EPR example with the two particles, and ask what if it is Alice (Albertina) who performs a measurement on the distant particle? She interacts with the undisturbed state (12) (with $p_0 = 0$, and suitable $x_0 \neq 0$), possibly even at spacelike separation to Bob's measurement on the nearby particle. (Recall Ehrenfest's words: the particle is 'flying about in isolation "on its own"'.) Why should *his* cutting himself off from the other components of the state force *her* to interact only with the particular $|x\rangle$ he has access to (or its momentum components)? Consider especially that one of the strengths of Bohr's account is that Bob's choice takes place entirely locally, i.e. it is because of something that happens with Bob at his own location that he is unable to interact any longer with all the components of the state (12) of the particle on Alice's side of the experiment.

The Everett theory of course has a ready answer: *nothing* forces Alice to interact only with one particular component $|x\rangle$. Indeed, she interacts with all of them, and if she also performs a position measurement, she splits accordingly into components that have each interacted with some particular $|x\rangle$, just as if Bob had not performed his measurement at all. Bob (more precisely, each of Bob's components) will only gain access to that component of Alice that has interacted with the $|x\rangle$ to which he himself has access; and similarly with Bob and Alice interchanged.[12]

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[11] As Hermann (1935) would put it, he is indirectly checking the causal connection established relative to the chosen context of observation by the original interaction between the particle and the diaphragm (or the electron and the photon in the case of the γ-ray microscope).

[12] If Alice performs a momentum measurement, things are only slightly more complicated: she will first split into components in which she registers a particular value $-p$; then, when she crosses the future light cone of Bob's measurement and can interact with any records of his measurement,

Bohr's complementarity view does not have such an answer ready.[13] Short of non-locality (observational contexts are determined by the first measurement to be performed in some privileged reference frame) or solipsism (observational contexts are determined only by me), the best answer appears to be that what should count as 'physical reality' depends holistically on the entire observational context, consisting of both Alice's and Bob's local contexts. One might ask, echoing EPR's conclusions, whether any 'reasonable definition of reality could be expected to permit this' (p. 780), but it would at least be an answer that keeps to the letter (if possibly stretching the spirit of) Bohr's entreaty that 'the unambiguous account of proper quantum phenomena must, in principle, include a description of all relevant features of the experimental arrangement' (Bohr 1958, p. 311).

Acknowledgements

I would like to thankl Elise Crull, my joint work with whom forms the background for this chapter; Hans Halvorson, who suggested our names as contributors to this volume; and Jan Faye and Henry Folse both for their invitation to contribute to this volume and for their patience in waiting for the result.

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she will split again (recall that a paradigm case of an observer splitting is precisely whenever they interact with the records of a measurement), so that now she has split into components that have registered some $-p$ on particle II and some x on particle I. When Bob interacts with Alice, he will interact only with those components of Alice that have registered his result x, but splits further himself (like Alice) to gain access to one particular one of these, characterised by some or other value of $-p$. (The quantitative explanation of the observed correlations follows from any account of probabilities in Everett.) For further elaboration of this spacetime formulation of Everett, see Bacciagaluppi (2002) (see also Wallace (2012, Chap. 8)).

[13] See Bacciagaluppi (2014) for a closely related criticism of qBism, the radical subjectivist approach to quantum mechanics developed by Fuchs (2010) (sometimes classed as a 'neo-Bohrian' view).

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