Bohm's Theory Cannot Ensure that Measurements have Unique Outcomes – A Study

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Abstract

This paper presents the Bohm's theory the measurement problem, recall, arises because quantum mechanics allows superpositions of arbitrary states. So for example, for a system containing a cat, if $|\text{alive}\rangle_c$ is a state of the system in which the cat is alive and $|\text{dead}\rangle_c$ is a state of the system in which the cat is dead, then the superposition state $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$ is also an allowed state of the system. It seems relatively straightforward to prepare a cat in such a state, for example using the apparatus of Schrödinger's famous thought-experiment (Schrödinger 1935). There is a recurring line of argument in the literature to the effect that Bohm's theory fails to solve the measurement problem. I show that this argument fails in all its variants. Hence Bohm's theory, whatever its drawbacks, at least succeeds in solving the measurement problem. I briefly discuss a similar argument that has been raised against the GRW theory The orthodox account of the import of the measurement problem in quantum mechanics goes something like this: The measurement problem shows that the standard theory of quantum mechanics is inadequate. Several strategies have been proposed to solve the measurement problem, and these yield various alternative theories of quantum mechanics, including hidden variable theories like Bohm's theory, spontaneous collapse theories like the GRW theory, and many-worlds theories like Everett's theory. These theories embody very different pictures of the world, so at most one of them can be true. The job of philosophy of physics, then is to assess the virtues and vices of the various solutions to the measurement problem, to determine which of them is the *best* solution (Albert 1992, ix). Against this orthodoxy, however, there is also a recurring heresy, according to which there has only ever been one adequate line of response to the measurement problem, and that is the many-worlds strategy.

Key words: GRW theory, Bohm's theory, measurement problem, Quantum Mechanics.

Introduction

This paper compares the three most popular ways of addressing the measurement problem, so let me begin by outlining each of them briefly. The material is familiar, but it will be useful to introduce a uniform terminology for describing the three theories, and to make explicit various assumptions I make for the sake of argument. For example, a realist attitude towards quantum mechanics is a presupposition of this paper. That is, the quantum state $|\psi\rangle$ is to be regarded as a description of the objective state of the world, in terms of the distribution of wavefunction-stuff over configuration space. The wavefunction itself can be regarded as something like an objective field. This position is not without its problems—most notably because the wavefunction for an *n*-particle system occupies a 3*n*-dimensional space—but these problems will be set aside here. I also presuppose that the state can be written down as a sum of discrete *terms*, where each term represents a more-or-less distinct *branch* of the wavefunction. This raises tricky issues concerning decoherence and the existence of a preferred basis, which again I set aside.

Objective

The chief motive of this paper is to unravel the myteries of Bohm's model in wave mechanics

Crux of the Matter

Von Neumann sought to explain our experience by proposing that the superposition collapses on measurement to one or the other determinate state (von Neumann 1932, 186). However, this strategy introduces the term "measurement" into the dynamical laws of fundamental physics, and this is widely regarded as unacceptable, both because "measurement" is a vague term, and because measurement interactions are physical interactions like any other, and hence cannot follow new dynamical laws (Bell 1987, 117–8).

In order to solve the measurement problem, then, we need an account of the determinacy of our experience which does not refer to "measurement" as an unanalyzed primitive. There are several major approaches to this problem. The spontaneous collapse approach is exemplified by the GRW theory (Ghirardi, Rimini and Weber 1986). According to the GRW theory, each fundamental particle has a small probability per unit time of undergoing a collapse process in which the wavefunction is multiplied by a narrow Gaussian in the coordinates of that particle. The Gaussian is centered on a random point whose probability distribution is a function of the wavefunction amplitude. This process has little effect on the evolution of systems of a few particles, because the probability of a collapse for such systems is small. But for a macroscopic system like a cat, the probability of a collapse becomes overwhelmingly large, even over very small timescales. This has the effect that a symmetric superposition state like $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$ rapidly evolves to a highly asymmetric state $a|\text{alive}\rangle_c + b|\text{dead}\rangle_c$, where either $|a|^2 >> |b|^2$ or $|b|^2 >> |a|^2$. That is, one branch of the wavefunction becomes very *large*, and the other becomes very *small*; it is the large branch that accounts for our determinate experience.

The hidden variable approach to the measurement problem is exemplified by Bohm's theory (Bohm 1952). Bohm's theory contains no collapse process; instead, it denies that the quantum state constitutes a complete description of a system. That is, in addition to the wavefunction distribution over configuration space, one must also specify a *point* in configuration space, which can be regarded as encoding the positions of a set of particles. In other words, the ontology of Bohm's theory includes both a wavefunction *and* a set of particles. The particles move according to a new dynamical law, such that one branch of the wavefunction is always associated with all the particles. So for a superposition like $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$, one branch will be *occupied* by particles and the other branch will be *empty*; it is the configuration of particles that accounts for our determinate experience.

The many-worlds approach to the measurement problem was founded by Everett (1957). This approach postulates neither a collapse process nor additional ontology; hence the state $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$ is stable and constitutes a complete description of the system. The adherents of this approach point out that the two branches of the wavefunction evolve almost completely independently of each other, and hence postulate that they can be regarded as parallel streams of reality, which they call *worlds*. Furthermore, they note that if a person were to observe the cat, the person's state would become entangled in the superposition, resulting in a final state $2^{-1/2}(|\text{alive}\rangle_c|\text{sees-alive}\rangle_p + |\text{dead}\rangle_c|\text{sees-dead}\rangle_p)$, where $|\text{sees-alive}\rangle_p$ and $|\text{sees-dead}\rangle_p$ are states of the person in which she sees a live cat and a dead cat respectively. In the idiom just introduced, we can say that in one world the person sees a dead cat, and in the other she sees a live cat. In other words, the person has now split into two copies, one in each world. Given that branches can be identified as worlds, and that a person's experiences can be specified relative to a world, the many-worlds theory explains why we always experience cats as either determinately alive or determinately dead.

There is no consensus concerning which of these theories (if any) constitutes an *acceptable* solution to the measurement problem, since each faces considerable difficulties that may eliminate it as a tenable physical theory. Still, it is usually conceded that each of them *is* a solution to the measurement problem, in the sense that it provides an account of the determinacy of our experience, even if this account may ultimately prove untenable. However, this concession has been challenged. In the following section, I present a recurring argument that Bohm's theory in fact fails to solve the measurement problem, together with a related line of argument aimed at the GRW theory.

The Basic Argument

The form of the argument against Bohm's theory is straightforward. Bohm's theory does not involve any collapse of the wavefunction, so even after the cat is observed, the state of the cat contains an "alive" term and a "dead" term. But the many-worlds theory, it is claimed, shows that these two terms constitute parallel branches of reality, containing a live cat and a dead cat respectively. Hence even if the "alive" branch is occupied by the particles and the dead branch is empty, there is still a dead cat, and Bohm's theory fails to ensure that our observation of the cat has a unique outcome. More generally:

(1) Empty branches are *worlds,* in the sense of the many-worlds theory.

(2) So empty branches contain measurement results.

(3) So Bohm's theory cannot ensure that measurements have unique outcomes.

(4) So Bohm's theory fails to solve the measurement problem.

If this argument is correct, then the particles in Bohm's theory are entirely redundant, since branches contain measurement results whether they are occupied or empty. The only sense in which Bohm's ("pilot-wave") theory solves the measurement problem is that it reduces to the many-worlds ("parallel-universes") theory;

hence Deutsch concludes that "pilot-wave theories are parallel-universes theories in a state of chronic denial" (1996, 225). The key premise is clearly the first one, and there are several different arguments in the literature that attempt to establish that empty branches are worlds. I address these arguments in the following two sections.

A similar argument has been leveled against the GRW theory. Even though the GRW theory does involve wavefunction collapse, both terms in the cat's state remain after the cat is observed, although one is much smaller than the other. Still, the many-worlds theory, it is claimed, shows that the two terms constitute parallel branches of reality whatever their respective amplitudes. Hence the above argument can be adapted to attack the GRW theory by substituting "low-amplitude branches" for "empty branches". Again, if the argument is correct, then the GRW collapse mechanism is redundant, since branches contain measurement outcomes whatever their amplitudes. The only sense in which the GRW theory solves the measurement problem, on this view, is that it reduces to a form of the many-worlds theory; there is "a Many-Worlds ontology at the heart of theories like … GRW" (Cordero 1999, S67). Again, the key premise is the first one—that low-amplitude branches are *worlds* in the sense of the many-worlds theory. I briefly examine an argument for this premise in section 6.

An obvious strategy for defeating the above argument in the Bohmian case is to claim that wavefunction-stuff is just not the kind of stuff from which objects like cats could be made, even in principle. One might even claim that the wavefunction is not any kind of "stuff" at all, but is merely a mathematical device for calculating the motions of the Bohmian particles. If either of these claims could be substantiated, then one would have a principled reason to deny that empty branches could contain cats, either dead or alive, or any other measurement outcomes for that matter.

Against this strategy, however, Deutsch writes of the empty branches (or "unoccupied grooves") that "it is no good saying that they are merely a theoretical construct and do not exist physically, for they continually jostle both each other and the 'occupied' groove, affecting its trajectory" (1996, 225). Since empty branches interact with each other and with the occupied branch, and empty branches are nothing but aspects of the wavefunction, the wavefunction must be real a physical entity and not just a mathematical construct. Brown and Wallace add that it is impossible to rule out a priori the possibility that ordinary physical objects could be made out of such an entity, even if it is fundamentally field-like (2005, 530). Furthermore, it is worth noting that such a strategy is not fully general, since it is not applicable to the GRW version of the argument. For present purposes, then, I do not question the underlying assumption that the wavefunction is a real physical entity, from which objects like cats might, in principle, be made.

Branches and Worlds

Even granting the reality of the wavefunction, though, it does not immediately follow that the empty branches in Bohm's theory are worlds in the sense of the many-worlds theory. That is, the first premise of the basic argument still needs justification. Several such justifications have been presented in the literature, but my contention here is that none of them succeeds. I examine three of these arguments in this section, and one in the next.

Deutsch argues that empty branches "obey the same laws of physics as the 'occupied groove' that is supposed to be 'the' universe. But that is just another way of saying that they are universes too" (1996, 225). There is certainly a sense in which the laws of physics are the same in empty and occupied branches; the wavefunction dynamics do not depend on the presence or absence of particles, and the particle dynamics do not *fail* in empty branches, although there is nothing for them to apply to. However, this is beside the point. Consider the state $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$, where one branch is occupied and the other is empty. In order for the empty branch to contain a dead cat, it must not only obey the same physical laws as the occupied branch, but it must also have the relevant physical state—the state that the occupied branch would have if it contained a dead cat. But the physical state of the empty branch is *not* the same as the state the occupied branch would have if it contained a dead cat. The wavefunction states of the two branches are the same, but according to Bohm's theory, the physical state of a system consists of its wavefunction state *and* its particle state. An occupied branch and an empty branch plainly do not have the same particle state, and hence Deutsch fails to establish that empty branches contain measurement outcomes.

Zeh's argument is similar: "Bohm's theory contains the *same* "many worlds" of dynamically separate branches as the Everett interpretation (now regarded as empty wave components), since it is based on precisely the same … global wave function" (1999, 200). It is true that the wavefunction structure is the same in Bohm's theory as in the many-worlds theory, but it does not follow that the empty branches in Bohm's theory are worlds. In the context of Bohm's theory, objects are (prima facie, at least) made out of Bohmian particles, so the fact that two branches have the same wavefunction structure does not establish that they contain the same objects. But if an empty branch does not contain the same objects as an occupied branch, it is hard to see in what sense it is the same world. Since Zeh provides no reason to think that the wavefunction alone determines the contents of a branch, his argument begs the question against Bohm's theory.

Wallace attempts to justify the claim that empty branches contain the same objects as occupied branches by appealing to a condition he calls Dennett's criterion: "A macro-object is a pattern, and the existence of a pattern as a real thing depends on the usefulness … of theories which admit that pattern in their ontology" (2003, 93). Wallace uses this criterion to argue that in the superposition state $2^{-1/2}(|\text{alive}\rangle_c + |\text{dead}\rangle_c)$, each branch contains a real cat: "In each of the branches there is a 'cat' pattern, whose salience as a real thing is secured by its crucial explanatory and predictive role" (2003, 97). This is the case even if one branch is occupied by particles and the other is empty, since "cats and all other macro-objects can be identified in the structure of the wave-function just as in the structure of the corpuscles", and "the patterns which define them are present even in those parts of the wave-function which are very remote from the corpuscles" (2003, 99). That is, a branch instantiates the same pattern whether it is occupied or not; the only difference is that in the occupied branch the pattern is instantiated in the evolution of both the wavefunction and the particles, whereas in the empty branch it is instantiated in the evolution of the wavefunction alone. So since objects in general are patterns, and the pattern is independent of the presence of particles, Wallace concludes that branches contain the same objects whether they occupied or not. Hence empty branches count as worlds in the many-worlds sense.

Wallace's argument is clearly an improvement on the previous two, since it gives a *reason* to think that the presence of particles is irrelevant to the contents of a branch. The appeal to patterns (plausibly, at least) provides a level of description that is neutral between occupied and empty branches. Of course, the relevant sense of "pattern" has to be carefully defined—there are many ways in which the particles and the wavefunction instantiate *different* patterns—but there is no reason to think this cannot be done. Assuming, then, that Dennett's criterion is sufficient to establish that branches are worlds, the remaining question is whether this means that Bohm's theory fails to solve the measurement problem.

I think that it does not, because there is another possibility that must be taken seriously, namely that to entertain Bohm's theory is to entertain the falsity of Dennett's criterion. The many-worlds theory is consistent with Dennett's criterion, in that a pattern in any kind of micro-physical stuff could in principle constitute a macro-object—although in fact there is only wavefunction-stuff. Bohm's theory violates Dennett's criterion in that it presupposes that macro-objects are tied to a particular kind of micro-physical stuff; a pattern in Bohmian particles can constitute an object, but the analogous pattern in wavefunction-stuff cannot. But then given that the Bohmian solution to the measurement problem presupposes the falsity of Dennett's criterion, Dennett's criterion cannot be taken for granted in arguing that Bohm's theory fails to solve the measurement problem.

Note that I am not arguing that Dennett's criterion is false. Dennett's criterion is part of a well-entrenched functionalist tradition in philosophy, and is arguably as securely established as any philosophical position. Rather, my point is that *every* proposed solution to the measurement problem succeeds at solving the problem only if it is allowed to violate some well-entrenched position or apparently obvious truth. The many-worlds theory is no exception in this regard. If it is to solve the measurement problem, it must explain how observers obtain determinate results to their measurements, distributed according to the usual quantum mechanical statistics. In order to do this, it must deny some well-entrenched assumptions concerning persons and probabilities, for example, that a person at a time has at most one future successor, or that probability requires uncertainty. Indeed, Wallace himself argues that the many-worlds theory requires us to give up the apparently obvious a priori truth that uncertainty presupposes some fact about which we are uncertain (Wallace 2005). If we refuse to give up any of these assumptions, then the many-worlds theory fails to solve the measurement problem.

Suppose the tables were turned; a Bohmian who took for granted all our intuitive views about probability and identity argued and argued on that basis that the many-worlds theory fails to solve the measurement problem would rightly be accused of begging the question against the many-worlds theory. This is because the many-worlds solution is predicated on the rejection of some or other of our intuitive views. But then by the same token, the fact that Bohm's theory fails as a solution to the measurement problem given Dennett's criterion should not be held against it, since Bohm's theory is predicated on the rejection of Dennett's criterion. Hence the many-worlds theory is in exactly the same boat as Bohm's theory; each theory solves the measurement problem only at the expense of at least one well-entrenched assumption. But a problematic solution to the measurement problem is still a solution, and much of the recent debate in the philosophy of physics concerns whether these problematic theories can be accommodated within philosophy and physics. Wallace clearly recognizes this in the case of the many-worlds theory, since he acknowledges the philosophical problems generated by the theory, and much of his work involves various attempts to address them (e.g. Wallace 2002; 2003; 2005). But then surely the same status should be accorded to Bohm's theory; it is problematic, to be sure, but it is as much a solution to the measurement problem as the many-worlds theory.

Of course, the problems facing the two theories are very different. Bohm's theory requires us to hold, contra Dennett's criterion, that macro-objects are essentially tied to a particular micro-physical structure; they are patterns in Bohmian particles, and not in wavefunction-stuff. The many-worlds theory, depending on how it is formulated, requires us to adopt various heterodox views concerning personal identity and probability. Perhaps one kind of problem is more serious than the other, and perhaps their respective problems render one or both theories untenable; this is a matter of ongoing philosophical debate. Nevertheless, they both solve the measurement problem, in the sense that *given* their problematic assumptions, each provides an explanation of the determinacy of measurement outcomes.

Theory and Interpretation

Deutsch, Zeh and Wallace each offer a fairly direct argument that the empty branches of Bohm's theory are worlds in the sense of the many-worlds theory. If the foregoing is correct, though, none of these arguments succeed. Brown and Wallace (2005) offer a more indirect argument for the same conclusion, to which I now turn.

Conclusion

Bohm's theory and the GRW theory each face serious difficulties, most notably regarding compatibility with special relativity, and each may turn out to be inadequate as a quantum mechanical theory (Bell 1987, 206). Perhaps one should add to these difficulties that neither theory is compatible with strict functionalism about macroscopic objects (Dennett's criterion). But if the foregoing is correct, then neither can be ruled out on the grounds that it fails to do what it was designed to do, namely to solve the measurement problem. And neither can be ruled out on the grounds that the solution it provides reduces to that provided by the many-worlds theory. Of course, the many-worlds theory also provides a solution to the measurement problem, and it too faces serious difficulties, most notably regarding personal identity and probability, but perhaps also regarding compatibility with relativity (Barrett 1999). So the business of comparing the various strategies for solving the measurement problem goes on, and the many-worlds theory cannot claim to be the winner by default.

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