On the Supposed Surrealism of Bohmian Mechanics

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In a recent paper, Englert et al. reject Bohm's reinterpretation of quantum mechanics as "surrealistic." Responses to this by Dewdney et al. and Durr et al. have generally missed the point of this somewhat strange characterization of the interpretation.

In this paper I explain the experiment which is supposed to illustrate the surrealism. I argue that what is really being objected to is the non-locality of the interpretation. While this is an undesirable feature of Bohm's interpretation, it is not a feature of which the standard interpretation gives a more satisfactory account.

In the synopsis to their paper "Surrealistic Bohm Trajectories", Englert et al. claim that they will demonstrate "that the trajectories, which David Bohm invented in his attempt at a *realistic* interpretation of quantum mechanics, are in fact *surrealistic*, because they may be macroscopically at variance with the observed track of the particle" [1]. The image they have in mind is that of the path a particle marks out in a bubble chamber. Their claim is that there is no guarantee that the trajectory called real by Bohm's interpretation of quantum mechanics will be the one observed in the bubble chamber. The bubble chamber problem is not easily solved, so they instead turn to simpler examples which feature pairs of measurements in the place of the continuous tracks of the bubble chamber. By appealing to certain symmetry properties of Bohm's interpretation they argue that the Bohmian trajectories cannot be accepted as real.

The second of their thought experiments is simpler, more practical, and taken up in a response by Dewdney et al. [2], so that is what I will discuss here. In the experiment of Fig. 1, an atom is sent through a section of a Stern-Gerlach apparatus. Initially the detector deflects spin-up particles up (in the positive z direction) and spin-down particles down. Farther along in the interferometer, the magnetic field is reversed so that, after point (1) on the x-axis of Fig. 1, the spin-up particles move in the negative z direction. The two possible particle paths converge at the point marked (2) on the x-axis and are then detected by a screen at point (3). According to standard quantum mechanics, a reading below the central axis will correspond to a

reading of spin $+1/2$ while a reading above the axis means spin $-1/2$. If the atom is initially in a superposition of spin states, then standard quantum mechanics describes this in terms of a probability wave which follows both paths until the atom hits the screen at which point it will have spin up (spin down) if it is detected below (above) the x-axis in which case it will be as if it passed through (1) above (below) the x-axis. Of course according to standard quantum mechanics it makes no sense to ask along what path the particle actually traversed. What is meant by the phrase "as if it had travelled a given path" will become clear later.

If we apply the Bohmian interpretation to the spin eigenstates we get the same result as with standard quantum mechanics. If, however, we apply the interpretation to the superposition state, Englert et al. argue that we will get trajectories that contradict the standard picture above. I will give a simpler version of their argument.

Bohmian mechanics claims that real particles will be propelled along trajectories determined entirely by the positions of the particles and the wavefunction which impels them. The first principle that follows from this is since the wavefunction is symmetric about the x-axis as are the possible starting positions of the atoms, the possible trajectories will be symmetric about the x-axis. Secondly, since the wavefunction and the position of the particle at any time determines the whole trajectory of the particle past and future, there can be no crossing trajectories. If particles with the same wavefunction were to agree at a single point, the determinism of the theory would require that they agree at all points both past and future. If we put these two principles together it becomes clear that no parti-
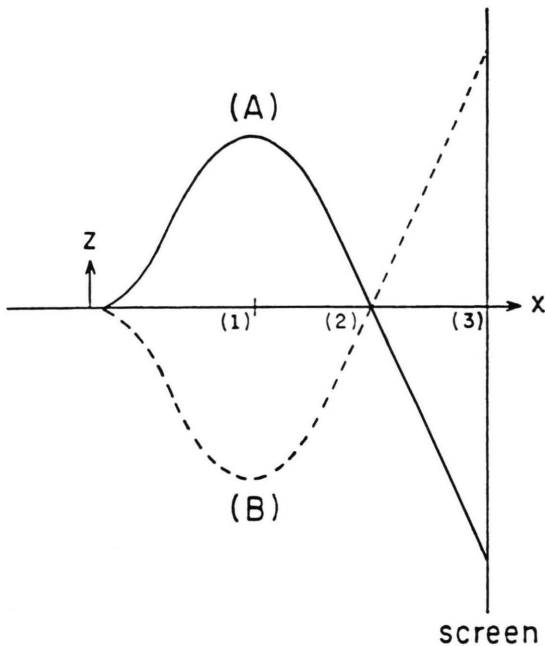
Fig. 1. The "as if" trajectories of standard quantum mechanics. The upper solid line corresponds to spin $+1/2$ while the dotted line represents spin $-1/2$.

cles can cross the x-axis. If a trajectory did cross the x-axis by the symmetry condition there must be an associated trajectory which crosses the axis in the other direction. But clearly these trajectories would cross through a single point which we know is impossible. So according to Bohmian mechanics, particles which cross (1) above the x-axis hit the screen above the x-axis and particles which cross (1) below the x-axis hit the screen below the x-axis.

At this point all we have created is a conflict between the real trajectories Bohm's interpretation posits, and the "as if" trajectories of standard quantum mechanics. Englert et al. believe they can turn this into a real conflict by recording the position of the particle at (1) and then reading off that position after the particle registers on the screen. They propose to do this with a pair of *micromaser* detectors. The basic idea behind the micromaser detector is to create a cavity with a known resonance frequency. This allows the cavity to absorb some precise amount of energy with near certainty. In this case the energy chosen is the transition energy for a Rubidium atom. Before the atom enters the detector it passes through a laser which puts it into an excited state. If it passes through the detector, the cavity takes this photon and returns

it to the relaxed state. The presence of this photon can then be measured by passing a second particle through the cavity and measuring the final state of this particle in any normal measurement fashion.

In the thought experiment, a detector is placed in each of the possible detector paths at (1) [call the top detector (A) and the bottom detector (B)] in such a way that according to standard quantum mechanics the possible joint eigenstates for the system [atom, (A), (B)] will be atom [$+z$ at (3) spin down], (A) = no, (B) = yes; and atom [$-z$ at (3) spin up], (A) = yes, (B) = no. The detectors are non-disturbing in the sense that they do not change the probability distribution for the atom. This does not violate the uncertainty principle of quantum mechanics because the position of the atom at (1) commutes with the position of the atom at (3). So we can known the position of the particle at both places.

So according to the standard interpretation of quantum mechanics, if the atom registers on the screen below the x-axis, then the top one-bit detector will be excited while the bottom one is not. Therefore we can, without fear of contradictory evidence, say the atom passed through the upper detector. This is true despite the fact that the wavefunction for the atom at that time was a superposition of the two position states. The situation is of course exactly reversed if the particle is detected above the x-axis (this is shown in Figure 1).

For the Bohmian interpretation, Englert et al. give the same argument to show that the Bohmian trajectories are unchanged. The wavefunction is still symmetric, there still can be no crossing patterns, the probability distribution is unchanged, so the Bohmian trajectories will be the same. So for Bohm, the particle which passes through (A) will hit the screen above the x-axis and the particle which passes through (B) will hit the screen below the x-axis (see Figure 2). They sum up the situation as follows, "[I]f an atom hits the lower screen [below the x-axis], it has left a trace in the upper detector. It's Bohm trajectory, in contrast goes through the lower detector. Likewise, an atom arriving in the upper region ... went through the lower detector, but its Bohm trajectory through the upper one. The actual tracks and the Bohmian trajectories could not be more at variance than that" [1, p. 1182].

The main thrust of the response by Dewdney et al. is to show that the above account of Bohmian Mechanics is too simple because it is based on a misconception of how the trajectories are to be derived. The
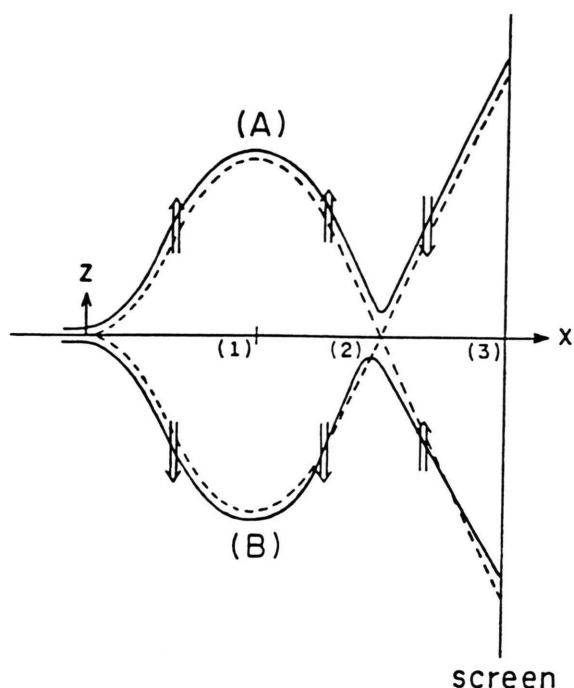
Fig. 2. The Bohm trajectories in the absence of a measurement. The spin value of a particle is reversed at (2).

Bohm interpretation posits only a single wavefunction for the entire universe. Obviously, if we had to know the wavefunction for the entire universe to solve problems, the interpretation would be useless. But when the wavefunction for some subsystem of the universe is essentially independent of that of the rest of the universe, then we need only concern ourselves with the wavefunction for those degrees of freedom which we care about or which are correlated with the value of those degrees that we care about. The trick in solving a problem using Bohm's interpretation will generally be to determine which degrees of freedom are relevant to the problem at hand.

The Englert et al. thought experiment without the detectors depends upon only the z component of the test atom plus the x component, which stands in as a measure of time, to determine the atom's evolution until it hits the screen. Accordingly, the Englert et al. account of the thought experiment without detectors is correct.

Once we add the detectors, however, we have to worry that we have added another degree of freedom associated with the detectors. Accordingly, to specify the thought experiment with detectors we will need to consider not just the x, z components of the test atom, but also a component y associated with the position of the measuring particles. So, the ban on crossing patterns will not be violated unless the particles cross the center axis, while the positions of the measuring particles remains the same. If the excitation of the micromaser cavity results in different positions for the particles that compose the cavity, then particles crossing the x-axis will have trajectories that are askew in configuration space. There will therefore be no self-interference of the wavefunction, and the standard trajectories will result. The Bohmian trajectories will be the same as the "as if" trajectories of standard quantum mechanics *.

Despite this observation, Dewdney et al. are not arguing that the Bohmian trajectories and the standard trajectories will always coincide. As we saw, they will not coincide in the absence of the detectors. They also will not agree if the excited state of the particle and the relaxed state of the particle are not captured by differences in the particles position [3, p. 8]. In such cases we will, in fact, get the trajectories for the test atoms which would result from the absence of the detectors. On the other hand, according to the Bohm interpretation, that the cavity is in an excited state cannot be an intrinsic property of the particles of the cavity alone since their only intrinsic properties do not change according to its energy state. That is to say that the energy state of the measuring particle is not a function of the positions of the measuring particles alone, rather it is an irreducible function of the position of the test atom as well. That the cavity is excited will correspond to a non-local relation between the cavity and the position of the test atom. The cavity is excited if it lies on the side of the x-axis with the test atom before (2) or across from the test atom when the atom is past (2) (at least until a measurement is made on either the cavity or the atom which will require inclusion of additional degrees of freedom pertaining to the measuring apparatus). That this is the excited state of the measuring particle follows from considering the result that would be obtained by sending a second particle through the cavity and determining its energy. That is, Bohmian mechanics predicts that, if the test atom's trajectory remains always below the

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* It should be noted that this consideration is enough to show that the image of the bubble chamber, with which Englert et al. begin their paper, is not an accurate one. The fact that the bubbles are correlated with the position of the particle being measured will be enough to prevent the non-crossing rule from applying.

x-axis, then after it has passed (2) the detector at (A) will be excited, while the detector at (B) will not. So despite the odd trajectories, Bohmian mechanics predicts exactly the same experimental results as does standard quantum mechanics.

If we take the claim of the Englert paper to be that Bohmian mechanics is empirically distinguishable from quantum mechanics and therefore wrong, the Dewdney response shows that this is not the case for the example considered. But despite some rhetoric which points in this direction, Englert et al. acknowledge that the two views are empirically equivalent. They describe the apparatus as providing "an experimentum crucis" [1], but not one that will prove Bohm's interpretation false. Rather, it is to show that "the reality attributed to Bohm trajectories is rather metaphysical than physical" [1]. When they talk about actual paths of atoms, they are in fact always talking about the positions of measuring apparatus rather than real positions of atoms. Dürr et al. focus on these points in their criticism. An "advocate of quantum orthodoxy would presumably have preferred the clearer and stronger claim that BM is *incompatible* with the predictions of quantum theory, so that, despite its virtues, it would not in fact provide an explanation of quantum phenomena. The authors are, however, aware that such a strong claim would be false" [3]. Both of the responses to Englert et al. criticize them for their failure to take into account the contextuality of measurement. But none of the papers, for or against, do a good job of drawing out what the Englert criteria of reality is supposed to be, and to what degree it has or lacks force. The rest of this paper will be an attempt to bring these issues out more clearly.

The clearest statement of what they mean by reality comes in the reply to the comment by Dürr et al. "[O]ne cannot attribute reality to the Bohm trajectories, where reality is meant in the phenomenological sense ... If the trajectories of BM have no relation to the phenomena, in particular to the detected path of the particle, then their reality remains metaphysical" [4]. This definition seems a bit strange since phenomenalism is usually contrasted with realism rather than taken as defining it. Realism is generally taken to be the view that things exist independently of whether they are or can be observed. It is also not true that the Bohmian trajectories bear no relation to the phenomena. They bear the natural relation needed for measurement, namely strict correlation.

There are three motivations that might be behind the Englert et al. denial of realism. The first is the degree to which their experimental set-up establishes the hidden nature of Bohm variables. The second is the strong non-locality of Bohm's interpretation. Finally, related to this is the essential holism or non-reducibility of intrinsic properties.

In one of his defenses of Bohmian mechanics, John Bell said, "Although Ψ [the traditional wavefunction under Bohm's interpretation] is a real field it does not show up immediately in the result of a single 'measurement,' but only the statistics of many such results. It is the de Broglie-Bohm variable X that shows up immediately each time. That X rather than Ψ is historically called a 'hidden' variable is a piece of historical silliness" [5]. The Englert example as corrected by Dewdney et al. shows that this is not always true. To know what X value is being measured we will sometimes have to already know ψ. We get this by averaging over the position measurements x, where x is the standard quantum mechanical variable, but it need not be the Bohmian position.

Putting it this way somewhat oversimplifies the differences between Bohmian mechanics and quantum mechanics. After all, measurement of microscopic properties is by its nature never direct. Even if the Bohmian trajectory coincided with the position of the detector which fires, we would still need the theory to tell us what standard quantum mechanical value we have measured. We will have to send the second particle through the micromaser detector and determine its energy by converting our problem into a position measurement. From this we use the theory to reason backwards to determine what initial state of the measuring particle would have produced this position value.** In the same way we reason backwards from the state of the micromaser cavity to the position of the test atom it recorded using the quantum wavefunction. The difference between the two reasoning processes then does not depend on the directness or theory-ladenness of the measurement, because neither measurement is direct and both are theory-laden.

The real difference Englert et al. are pointing to is that in standard quantum mechanics we can reason back using only local connections while in the case of

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** It might be argued that we do not reason back using standard quantum mechanics, rather we reason back using classical mechanics or classical reasoning. This seems to be a rather strange defense, though, given that such reasoning is not generally reliable in the quantum domain.

Bohm's interpretation we need non-local connections as well. In their Reply to Comment, they contrast Bohmian mechanics unfavorably with "standard quantum theory with its short range interactions only" [4].

The locality*** of standard quantum mechanics would seem to be a contentious issue at best. A large part of the question comes down to what phenomena one feels need to be explained. According to standard quantum mechanics, the wavefunction of a particle can be non-zero over all space, but a position measurement will collapse the wavefunction to some localized region of space. Such a change would not seem to count as a localized interaction. However, Englert et al. can dismiss such an example because they believe that "the significance of Schrödinger's wave function [is] as a tool used by theoreticians to arrive at probabilistic predictions. It is quite unnecessary, and indeed dangerous, to attribute any 'real' meaning to the ψ-function" [4]. So non-local changes in ψ will not count against the locality of the theory because they are not changes in real elements of the theory.

The problem with such a move is that if we dispense with the reality of the wavefunction of the test atom and measuring system as well as with all hidden variables, then it is not clear what the existence of these particles consists in. And yet it is these microscopic particles that are engaging in the local interactions that they talk about. After all, the observable phenomena do not interact directly at all and certainly not locally.

Some standard interpretations try to get around this by assigning propensities of positions to particles which are not in well-defined position states, but ascribing a property only when a value can be predicted with certainty. But even such a minimal attribution of properties will be inconsistent with the Englert et al. locality condition. Suppose we imagine the Englert et al. thought experiment with the final screen removed so that the test atom is allowed to proceed unmeasured. We can then measure the excitation state of the detector (B) at some time t after the test atom is far away. This will drive the detector (A) into a well defined state at t despite the fact that there is nothing locally interacting with it at t.

*** By locality I mean to be capturing the Englert notion of "short range interactions only." I am not relying on any distinctions between strong and weak locality, or locality and separability, etc.

It is hard to see exactly what the locality of standard quantum mechanics means for Englert et al. The test atom and the measuring particle exist because they can be directly (and apparently locally) measured, the latter by some unspecified measuring apparatus, and the former by the latter. But to say that these interactions are local seems to imply that we can attribute locations to the objects which are interacting. If we have a particle crossing a bubble chamber creating a visible path it may make sense to say that we can directly "see" that it is there. We can imagine that the position of the released measuring particle is to be measured in something like this manner and therefore that during this measurement it has a real position which is determined through local interactions. But the interaction between the test atom and the measuring system is clearly not of this type. After the interaction, and prior to the measurement of one or the other of them, we can not know with certainty where the test atom is. Nor can we in any sense directly observe the position of the particle or the excitation state of the measuring system. We cannot ascribe a localized position to the test atom without invoking a well hidden variable of the type we have ruled out. The best we can do is to invoke the "as if" trajectories or consistent histories of the particles to show that the interactions could have occurred locally if our existence criteria was slightly suspended. So the standard interpretation's advantage with regard to locality seems questionable at best. While Bohm's interpretation is non-local, the standard interpretation makes the question of locality poorly defined.

A final issue that seems worth mentioning, although it does not come up explicitly in the papers in question, is the non-reducibility of properties of pairs of particles to properties of the individual particles. This has the result that it may be misleading to talk about interactions in terms of causes and effects. Consider the Englert et al. thought experiment where the excitation state is not dependent on the position state of the micromaser cavity. In their paper, Dewdney et al. show that the particle which passes through (B) will hit the screen below the axis leaving the detector (A) in its excited state. This implies that at some point there is a transfer of energy from the test atom to the detector. We know that the state of both detectors is relaxed until the test atom crosses (1). After (1) we will always find one detector excited and the other relaxed. This might lead us to believe that the transfer of energy occurs when the particle crosses (1). That is to

say, a quantum of energy is transferred non-locally from the test atom to detector (A) when the test atom crosses (1). This is, however, inaccurate. It is easy to see that a measurement of the detectors while the test atom is between (1) and (2) will find detector (B) excited and detector (A) relaxed. This follows because the measurement of either detector will make the excitation state of the particle dependent upon the position of the particle. As we have already seen, this has the effect of destroying the wavefunction's self-interference and producing the "as if" trajectories. So the actual evolution has a local transfer of energy from the test atom to detector (B) followed by a non-local transfer of energy from detector (B) to detector (A) when the test atom crosses (2). (Alternately we can posit a transfer of energy from detector (B) back to the test atom and another transfer from the test atom to detector (A) when the test atom crosses (2). This would explain why the presence of the second detector is superfluous to the experiment.) We can also say that there is no transfer of energy until the photon in the micromaser is itself detected, whenever that may be. After all, the excitation state does not depend upon any property of the atom until then. What all of these possibilities suggest is that the energy lies in the particle pair (or triplet) until some interaction destroys their correlation. Any attempt to break the energy distribution down further will be essentially arbitrary. This is true because ultimately the energy is determined by the wavefunction which does not reduce to independent parts corresponding to the individual particles. It also stresses the degree to which the wavefunction must be treated as a real object under Bohm's interpretation.

The effect of this irreducibility is what leads Englert et al. to say that there is no correspondence between the test atom's trajectory and the detector reading. We won't be able to posit general laws like "if an atom crosses a certain distance from a detector it will fire." Instead we will always have to abstract out to the joint wavefunction and note that this trajectory coincides with the detector firing while that trajectory does not. This seems to me to represent the biggest conceptual difference between Bohmian mechanics and classical mechanics. Newtonian mechanics contained action at a distance and unverifiable properties, but central to the theory was the idea that all forces acting on a given object can be traced back to intrinsic properties of the other objects that it interacted with. This fails to be the case with Bohmian mechanics.

The Englert et al. experiment illustrates some surprising, and perhaps undesirable, features of the Bohm interpretation of quantum mechanics, but as I have shown, these are not features about which the standard interpretation gives a particularly satisfying account. These are also features which the adherents of Bohmian mechanics have already acknowledged. So while the Englert et al. thought experiment does a good job of bringing out the subtleties of the interpretation, it does not give a compelling reason for abandoning it. This is particularly true in the absence of a discussion of the desirable features of the theory. It also does not justify the claim that the Bohm trajectories cannot count as realist ones.

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