Can Experiments Help us Choose Between the Bohm and Copenhagen interpretations of Copenhagen

By Lon Becker

Abstract: In this paper I will look at whether it is possible for experiments to help us decide between the Bohm and Copenhagen interpretations of quantum mechanics. I will look at experiments which assume that the two interpretations are empirically indistinguishable but highlight features that might lead us to favor one interpretation over the other. I will argue that such experiments are interesting but ultimately not convincing. I will then sketch an experiment to suggest how it might be possible to create an experiment which could distinguish between the two interpretations by focusing on the presence or absence of collapse.

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In this paper I will look at the degree to which quantum mechanical experiments can push us to accept or reject a particular interpretation of quantum mechanics. In this case I will be dealing with David Bohm’s realist interpretation. The issue will be broken down into two cases: suppose that the Bohm interpretation is empirically indistinguishable from the standard interpretation, can experiments give us reason to support one over the other? I will describe two such thought experiments, one which could be taken to favor the Bohm interpretation and one which could be taken to oppose Bohm. Ultimately I am of the opinion that while such experiments are interesting they are not likely to compel us to one interpretation rather than the other. The second question is, of course, whether the interpretations are in fact indistinguishable. I will describe an experiment which shows how there could be an empirical difference. The difference will not lie in making a different prediction than the standard interpretation, rather it will lie in making a prediction where the standard interpretation is ambiguous.

In the last ten years there has been an increasing interest in Bohm’s 1952 interpretation of quantum mechanics.(1) Some of the interest could be justified simply on the grounds that Bohm showed that it is possible to have a causal hidden variable interpretation of quantum mechanics, something which was at the time believed impossible, although this would not explain the delay in interest in the interpretation. Along these lines, James Cushing has argued that the fact that the standard interpretation of quantum mechanics is the Copenhagen interpretation rather than something like

Bohm's interpretation is a matter of historical contingency. We could have had Copenhagen, we could have had Bohm, the empirical content of quantum mechanics does not favor one over the other. (2)

On the other hand, that point having already been made thoroughly, the growing interest in Bohm's interpretation would seem to lie in the belief that we could someday have rational reasons for preferring Bohm to Copenhagen. What I mean by this is that we could find that in the long run (whatever time period that may be) we could discover that Bohm is preferable to Copenhagen because it has certain advantages which have not yet come to light, or at least have not been recognized for their importance. In particular, it could be the case that the attempts to flesh out the Bohm interpretation are important because future experiments may give us a reason for preferring it and it would be helpful to have a clear idea of what these two interpretations consist of so we are prepared to recognize these experiments when they arise (or even so that we can focus on devising them so they arise more quickly).

Below I will describe a couple of experiments which seem to favor one interpretation or the other despite not producing any variance in experimental predictions. The experiment favoring Bohm's interpretation will show how Bohm's interpretation has been used to solve a problem to which physicists have otherwise had trouble finding a satisfying solution. The experiment opposing the Bohm interpretation will show how the hidden trajectories of Bohm's interpretation can be at odds with what experiments seem to be revealing.

The first type of experiment to be described involves defining a quantity which physicists believe should be defined, but for which the standard interpretation offers no clear candidate. The problem concerns a particle approaching a potential barrier of finite width. Assuming that the energy of the particle is less than that needed to cross the barrier, classically the particle would simply reflect off of the barrier. But in quantum mechanics there is some probability that the particle will pass through the barrier. The quantities to be defined are the average time that a particle spends in the barrier region (* -Transit time), the time that particles that pass through the barrier spend in the barrier region ($*_T$- Transmission time), and the time that reflected particles spend in the barrier region ($*_R$- Reflected time).

The transit time * seems to be largely unproblematic (in the sense that there is general agreement). Since we want the average time spent by each particle in the barrier region we want to know how much of the wavefunction is in the region over time. This turns out to be equal to the average number of particles in the barrier region divided by the average rate of particles entering or leaving the region . (3)

The natural extension of this to transmission and reflection times would seem to be to determine which particles are going through and to apply the same calculation to get their transit time (and similarly with the ones that are reflected). The problem is that since the operator which separates the transmitted particles from the reflected particles does not commute with the operator described above to get the transit times, the resulting transmission and reflection times do not satisfy plausible probability relations. In particular if T is the percentage of particles transmitted and R is the percentage reflected we should expect that the total transit time $*=T*_T + R*_R$ (where $T + R = 1$). This simply makes the common sense claim that the average time spent in the region by all particles is the weighted average of the time spent by particles that go through and by particles that do not. This would be a tautology in classical mechanics because all of the particles either go through or do not go through. So the average of these two types of particles would have to be the average of the total particles. But in tunneling problems this will not generally be the case. The reason is that an operation which determines the transmitted and reflected portions of the wavefunction destroys the possibility of interference between these parts. But the value of * is dependent upon this interference, so this approach to determining $*_T$ and $*_R$ is unsatisfactory. Many alternative proposals as well as the reasons that they are unsatisfactory can be found in a 1989 review article by Hauge and Støvneng.(4)

Since Bohm's interpretation of quantum mechanics describes the world as having determinate particle trajectories, it follows that these three quantities must be well defined on the Bohm account. One need simply follow the total trajectories, the trajectories that pass through the barrier, and the trajectories that are reflected by the barrier, and see how long each group spends in the barrier region. Although not simple, this procedure can be carried out through computer modeling. Such an approach has bee proposed by Leavens and Aers.(5) It produces the expected value for *, and reasonable values for $*_T$ and $*_R$. In this way the Bohm interpretation produces the most satisfactory solution to the problem.

How should the supporter of the Copenhagen interpretation respond to this fact? It seems to me that the proper response is that given by Dumont and Marchioro(6), which is that the Bohm interpretation may give the nicest solution to the transmission/reflection time problem, but there is no reason to believe that the problem should have a solution to begin with. One cannot determine whether a single particle is transmitted and at the same time determine the time it spent in the barrier region. Therefore there is no reason to believe that a quantity which combines these two properties has a deterministic value. Bohm's interpretation assigns values to all kinds of properties that Copenhagen does not, but it doesn't "solve" these problems since there are in general no problems here to be solved according to the Copenhagen interpretation.

This response has particular appeal here when one considers how the Bohm interpretation is actually used to determine a value. According to the Bohm interpretation, no two trajectories governed by the same wavefunction can cross in space. This is true because the trajectories are determined by the wavefunction and the position alone. This means that any two trajectories which share position and wavefunction must evolve in the same way and so must be the same trajectory. Since the transit time problem is described in 1 dimension, the trajectories in the front of the wavepacket must remain in the front of the wavepacket, otherwise they would have to cross other trajectories. This means that if 40% of the particles are transmitted, they must represent the front 40% of the trajectories of the wavepacket as it approaches the barrier. We can then get the transmission time by applying the transit time procedure to the front portion of the wavefunction which represents the front 40% of trajectories. We get the reflection time by doing the same procedure with the rest of the wavefunction. Obviously these terms will be real and will average to the transit time since they are parts of the same calculation used to produce the transit time. These transit times can be described under the Copenhagen interpretation as coherent operators. But according to the Copenhagen interpretation there is simply nothing significant about them. They represent one of infinitely many arbitrary ways of dividing up the wavefunction in this case. It is only assumptions from the Bohm interpretation which Copenhagen rejects which makes these calculations significant.

What makes this example somewhat favor the Bohm interpretation is that the search for these quantities was initiated by physicists with no apparent interest in interpretative issues, most of whom if asked would probably claim to support the Copenhagen interpretation. If it is useful in building high speed devices to have values for these quantities then it is an advantage for Bohm's interpretation that it defines them while the standard interpretation does not. Of course it must turn out to be the transmission or reflection time which is useful as both interpretations agree on the transit time. However, this is a somewhat limited advantage as the quantity can be only indirectly useful. If it were ever directly measurable, then the two interpretations would have to give the same answer since here they both use the same equation.

Having considered an experiment which provides marginal support for the Bohm’s interpretation, it seems fair to consider one which provides similar opposition. If we show support for the Bohm interpretation by showing that its added structure can be useful in addressing problems in physics, it makes sense that we would undercut that support with an experiment which shows that the added structure is not merely superfluous, but intuitively at odds with the observed phenomena. An experiment of this sort has been proposed by Englert et al. In an attempt to show that Bohm’s interpretation is, in their words, “surreal rather than real.”(7)

The experiment makes use of a 3/4 Stern-Gerlach apparatus. When a beam of atoms is sent through the apparatus the particles with positive spin values are drawn upward, while the particles with negative spin values are drawn downward. The magnetic field of the apparatus is then reversed so that positive spin is pulled down and negative spin up. The two particle paths cross and hit a screen some distance away. The particles that were initially drawn upward hit the screen below the central axis while the particles that were initially drawn downward hit the screen above the central axis. Particles that do not enter the apparatus with determinate spin value follow a superposition of these two paths with the same portion of the wavefunction that is initially pulled upward ultimately hitting the screen below the axis. Intuitively we would say that the superposition case involves a combination of the two trajectories from the determinate spin states. The Bohm trajectories, however, do not behave this simply. This follows from the no crossing rule mentioned in the last section. Since each particle entering the apparatus is guided by a single wavefunction, any two trajectories that agree at a single point must be the same trajectory. But this implies that particles that are drawn upward cannot cross the trajectories of particles that are drawn downward. This means that if both spin values are equally likely, the particles that are initially drawn upward must hit the screen above the central axis while those that are initially drawn downward will hit the screen below the central axis. However, if for example, the spin up value is twice as likely as the spin down value, then 2/3 of the trajectories will initially be drawn upward, while 2/3 of the trajectories will hit the screen below the central axis. But they will not be the same 2/3 of the trajectories. All of the trajectories which are initially drawn downward will hit the screen below the axis, but of the trajectories that are initially drawn upward, half will hit the screen above the axis and half will hit the screen below it.

The idea of Englert et al. is to draw out the counterintuitive nature of these trajectories by adding detectors to the paths inside the apparatus. The quantum theory predicts that whenever a particle hits the screen below the axis, it will register in the detector that is above the axis (and vice-versa). Englert et al. are a bit too complacent in assuming that the addition of the detectors will not affect the Bohm trajectories, but Dewdney et al.(8) In a response to their paper acknowledge that creating the situation Englert et al. Imagine is possible, although more difficult than they suggest.

So in the problem with detectors (still imagining that spin up is twice as likely as spin down) the Bohm interpretation says that there will be particles that are initially drawn downward, hit the screen below the axis, but leave the upper detector having registered. Of the particles that are initially drawn upward, half will hit the screen above the axis leaving the lower detector registering a detection. The other half will pass through the upper detector, hit the screen below the axis leaving the upper detector registered. So 2/3 of the time the particle will not have passed through the detector that is left having registered a particle. Also, when the upper detector registers a detection, there is equal likelihood that the particle passed through it as that it did not.

Note, this is not an empirical problem for Bohm. It is a description of what Bohm's interpretation predicts. The empirical results are exactly the same as one would get from the standard interpretation. Rather what we have is a situation in which the underlying structure of the Bohm interpretation rather than clarifying the situation, further complicates it. Empirically we know that 2/3 of the time the particle will have the upper detector registering. Similarly 2/3 of the time we will have the particle hitting the screen below the axis. The Copenhagen interpretation says that this is because these particles were detected above the axis and then hit the screen below the axis. The Bohm interpretation agrees that the particle hit the screen below the axis, but denies that the detector and screen readings tell us anything about which detector the particle passed through. When the lower detector registers a detection this does tell us which detector the particle passed through, but it tells us it was the upper detector.

Putting it this way somewhat exaggerates the relative difficulty for the Bohm interpretation. For one thing it is not clear to what degree the standard interpretation can be consistently thought to ascribe properties to microscopic objects even when they are detected. The way that situations are often described in the standard interpretation as if things have occurred in a somewhat classical manner is often misleading. Also, if one follows the experiment more closely using the Bohm interpretation we can see that the passage of a particle through a detector always results in that detector registering the detection. If we were to test the detectors immediately after the particle passes through (meaning before it reacher the central axis) we will always find the expected detector having registered. What this experiment does is to set up controlled interference after the measurement occurs, but before the measurement is observed, which changes the measurement result. The final detector readings then reflect the result of interference when the parts of the wavefunction interfere at the central axis, rather than the simple passage of the particle through the detector. It is this interference that affects the detectors and gives the counterintuitive readings. But it is not surprising that interference changes the values of our detections. Still this is an example of a case in which the standard interpretation gives a simple straightforward explanation of the phenomena, while the Bohm interpretation gives a complicated account of the same phenomena.

Standard quantum mechanics is generally expressed in terms of two postulates, the Schrödinger equation, which governs the evolution of systems, and the projection postulate (or collapse), which governs measurements. Since the Bohm interpretation incorporates the Schrödinger equation, we cannot use the Schrödinger evolution to test between the two interpretations. This is illustrated by our two previous experiments. Instead, if we want to develop an experimental test, it must turn on the fact that the Bohm interpretation denies that there is any real collapse.

One difficulty in designing an experiment which depends essentially on the presence or absence of collapse is that the notion of collapse is somewhat ambiguous on the standard interpretation. On the one hand, a particle is thought to actually pass through the detector that detects it (as in the last experiment), at the same time collapse is associated with the macroscopic nature of the measurement. But a detection can be made a macroscopic phenomena long after the particle has left the detector. Finally, collapse is sometimes associated with the observation of the measurement by the observer. This, also, can occur at a different time than the other two stages of measurement. This ambiguity remains possible because of the lack of a test of collapse between these stages. By a test of collapse I mean establishing that after the measurement has progressed to a certain stage it is either possible, or impossible to reestablish interference between the parts of the wavefunction representing different collapsed states.

The problem is that the relevant wavefunction is defined over a configuration space that includes the state of the wavefunction. What this means is that we will have to be able to simultaneously manufacture interference in the detected particle and the detector, or more reasonable control the detector in such a way that it does not interfere with the interference of the detected system. It seems clear we will not be able to do this after an experimenter observes the result of the experiment. The complexity of the human brain seems to justify this claim. On the other hand, it seems quite plausible that we could erase the effects of a microscopic detection. Various proposals towards this end have been put forward by Scully et al. under the rubric of quantum eraser experiments.(9) But this would not generally be taken as a test of the standard interpretation as most adherents of the standard view would accept that interference could be restored at this level, at least in theory. The interesting question is whether we can erase the effects of a macroscopic detection. In this case the standard interpretation seems compatible with both results, and so favors neither. The Bohm interpretation has a determinate result, while the standard interpretation can be filled in to fit whatever results can be obtained. This seems to be to the credit of the Bohm interpretation if such a test is possible, although clearly it is not if such a test is not possible.

I have elsewhere proposed what I believe is an interesting candidate for such an experiment. The experiment makes use of a 3 crystal neutron interferometer which splits a neutron beam at the first crystal and recombines the parts at the third crystal if nothing has happened to destroy the possibility of interference between the crystals. We place a detector in each path which does not alter the trajectories of the two possible neutron paths (such a detector has been designed for other particles but is currently only a theoretical possibility for neutrons). If the neutron takes the upper path it will be detected by the upper detector. If the neutron takes the lower path obviously it will have a comparable affect on the lower detector. What this means is that when the neutron reaches the third crystal the detection result will be effectively recorded and there will be no interference between these two parts of the beam. Now suppose we send a second neutron with the same wavefunction through the interferometer. The neutron will either follow the same path as its predecessor or it will follow the opposite path. If it follows the same path then one detector will have detected twice while the other has not detected anything. Clearly this will not restore the interference. The interesting case comes when the second particle goes in the opposite direction from the first. In this case each detector has been detected once. In the two cases where the first neutron goes up and the second goes down, and in which the first particle goes down and the second goes up, we will have essentially the same final detectors states. This at least presents the possibility of a restoration of interference effects. The math is tedious, but not difficult and the result is that the form the interference would take is that given the two possible exit paths of the interferometer, with interference the second neutron would always follow the same path as the first neutron. In the absence of interference the final states would be uncorrelated. This is an empirically detectable effect.

Obviously the ultimate question is to what degree the final states being essentially the same is enough to restore interference. This is clearly a worry whenever we are talking about macroscopic interactions. Here though, we are only counting on the fact that the initial state of the detectors is the same regardless of what evolution the neutrons later take, which is a given. Secondly, that the state does not change too greatly in the time interval between the passage of the first and second neutrons. This is not a given, but is not unreasonable from the outset given that we have no reason to believe that the state of the detectors is in rapid flux prior to the detection interaction. The reasonableness of this will also depend upon the degree to which we can control the time interval between the passage of the two neutrons, which remains an open question. Another key assumption here is that we can control the state of the two neutrons so that they really are the same state. Again whether we can do this remains an open question, but at least we have focused what we are trying to control from a macroscopic number of particles, to the problem of controlling two particles. Note also that we do not really need the final states to be exactly the same, we only need them to overlap enough to get a detectable interference effect. I assume that if we could get the first particle to reliably follow the second 60% of the time, this would satisfactorily solve our challenge.

In this paper I have tried to give a survey of how empirical results or thought experiments could be used to influence our choice of interpretation between the Bohm and Copenhagen interpretations of quantum mechanics. Although I have only looked at three experiments, I think these represent the ways in which experiments could affect our choice, and probably as convincing examples as we are likely to develop.

The first experiment makes use of the essential addition of Bohm's interpretation to the degree that it is empirically indistinguishable from the standard view. This is the fact that it defines as meaningful quantities which the standard view considers meaningless. Since the two interpretations are here being considered as empirically indistinguishable, the quantity in question can at best be indirectly measurable. Here the result is that importance is placed on a mathematical operation on which Bohm's interpretation might place importance, but which there seems to be no reason why the standard interpretation would consider important.

The second experiment illustrates the counterintuitive nature of some of the quantities which Bohm considers significant but the standard interpretation considers undefined. This example makes use of all of the counterintuitive features of the Bohm interpretation, the non-locality, the essential use of configuration space, the trajectories whose oddness appears to have no cause in the world. But despite this it fails to show more than that the Bohm interpretation has these weird features. But this is a fact acknowledged even by the views proponents.

These first two experiments may give solace to one side or the other, but they seem unlikely to actually convince anyone to switch sides. This is because the difference in intuitions on both sides are stronger than the amount of weight that can reasonably be placed on these experiments lacking an empirical difference. It seems possible that opinion in the philosophy of science community is slowly shifting towards the Bohm interpretation and away from the Copenhagen interpretation, so it might be thought that even without an empirical difference we will eventually come to accept the advantages of Bohm over Copenhagen. But it is unlikely that a similar shift is occurring in the physics community, and there is no reason to believe that the current interest in realist interpretations will last. More likely, any significant shift in the realist direction will simply set off a counter movement back away from realism. Ultimately as long as the interpretations remain empirically indistinguishable I can't see either side effectively winning out, except to the degree that Copenhagen has currently won and gets to be called the standard interpretation.

The final experiment tries to come up with a way to empirically distinguish between the theories. It does this by looking at the one real mathematical difference between the interpretations, namely the lack of a projection postulate in Bohm's interpretation. It tries to address the problem of how an interaction can be both macroscopic and reasonably controlled to the microscopic level. It is very possible that the requirements needed to carry out such an experiment are simply impractical, and we will never be able to carry out an experiment to the necessary degree of accuracy. But it seems to me that this program carries enough promise of interesting philosophic consequences to make it well worth the attempt to fine tune it into a workable experiment.

References

Bohm, D. (1952), “A Suggested Interpretation of Quantum Theory in Terms of ‘Hidden’ Variables” Physical Review **85** :166-180

Cushing, J (1994), *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony* Chicago: University of Chicago Press

Dewdney, C, L. Hardy, and E. Squires (1993) “How Late Measurements of Quantum Trajectoriescan Fool a Detector” Physics Letters **184A**:6-11

Dumont, R and T. Marchioro (1993), “Tunneling Time Probability Distributuin” Physical Review **47A**: 85-97

Englert, B-G, M. Scully, G Süssmann, and H. Walther (1992) Surrealistic Bohm Trajectories” Zeitschrifft Für Naturforschung **47a**: 1175-1186

Hauge, E. And J. Støvneng (1989), Tunneling Times: A Critical Review” Reviews of Modern Physics **61** : 917-936

Leavens, C (1990), “Transmission, Reflection, and Dwell Times within Bohm’s Causal Interpretation of Quantum Mechanics” Solid State Communications **74**: 923-928

Leavens, C and G. Aers (1988) “Dwell Tomes and Phase Times for Transmission and

Reflection," Physical Review **39B** :1202-1206

Scully, M, B-G. Englert, and H. Walther (1991) "Quantum Optical Tests of Complementarity" Nature **351** 111-116