Are there observational differences between Bohmian mechanics and other interpretations?

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Abstract While there is a consensus that leading interpretations of quantum mechanics cannot be distinguished with today's technology, it is unclear if a gedanken experiment which relies on unlimited technological power cannot do so. Another gedanken approach is considering sentient beings which have brains different from ours. Such gedanken situations will be analyzed with emphasis on a possible difference between Bohmian mechanics and the many-worlds interpretation.

1 Introduction

I can see a parallel between Detlef Dürr's and my own work on the interpretations of quantum mechanics. For both of us this was a central part of our research and we both believed that there is a single interpretation which is much better than others. However, while Detlef had no doubt about the superiority of Bohmian mechanics (BM) [1, 2], I am certain that the many-worlds interpretation (MWI) [3] is by far the best. The term "interpretation" might not be precise: different interpretations of quantum theory are sometimes actually different theories. In this essay, I want to shed light on possible observational differences between different interpretations and, in particular, between BM and MWI, while it is not clear that such differences exist.

We make our observations using our senses which provide our experiences, and the next section defines the connection between ontology and experience. In Section 3 I start the analysis by gedanken attributing conscious experience to a microscopic particle, a neutron. The advantage is that we can consider experiments which are performed in laboratories. Section 4 is devoted to similar experiments with macroscopic sentient beings. Here, the gedanken story is the possibility to perform such

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experiments. The next level of gedanken consideration in Section 5 is to consider macroscopic sentient beings with brains operating using spin states.

2 Experience supervenience postulates

In my view, a theory (interpretation) consists of two ingredients: an ontology described in mathematical terms and a rule which provides correspondence between the mathematical formalism and our experience. I do not presuppose any complicated / refined meaning of the "experience" beyond a basic physicalist notion, where there is no conceptual difference between my experience and the experience of a robot equipped with various sensors.

For some theories, the rule connecting the ontology and experience seems trivial and frequently is not mentioned explicitly. For example, Newtonian mechanics supervenience postulate:

> The experience of a sentient being supervenes on the position and velocity of the particles it consists of.

Standard textbook quantum mechanics (which includes collapse of the wave function at every quantum measurement) supervenience postulate:

> The experience of a sentient being supervenes on the wavefunction of its degrees of freedom.

In these cases, the rules are trivial because they are based on the full ontology of the theory.

For BM and especially for MWI, the supervenience rule is an essential part of the interpretation. Indeed, the ontology of the MWI is the universal wave function, period. The same universal wave function is also part of the ontology of BM (although Bohmians often attach to it a lower status [1]). The BM supervenience postulate is necessary to avoid multiple worlds in BM.

The MWI supervenience postulate:

> The experience of a sentient being supervenes on the wavefunction of its degrees of freedom within the world branch of the wave function of the universe.

It is the same postulate as in the textbook quantum mechanics, in which there is only one branch of the universal wave function.

For BM I suggest considering two possible postulates. The BM supervenience postulate I:

> The experience of a sentient being supervenes on the Bohmian positions of the particles the sentient being is made of.

The BM supervenience postulate II:

> The experience of a sentient being supervenes on the Bohmian collapsed wavefunction of its degrees of freedom.

the Bohmian collapsed wave is unambiguously defined only when we have well-localized branches.

Another possible proposal is supervenience on both Bohmian position and the Bohmian collapsed wave function. However, I feel that every one of the ingredients, Bohmian positions or Bohmian collapse wave function is enough to explain our experience, so this proposal seems to be unreasonably complicated and not necessary.

3 Experiences of a neutron

I want to start by analyzing a neutron Mach-Zehnder interferometer (MZI), a device that already four decades ago was used as a test bed for the strange behavior of quantum systems [4], see Fig. 1. In the past I analyzed such an interferometer attaching “consiousness” to the neutrons and arguing that we need the MWI to avoid schizophrenic experiences of neutrons in the interferometer [5]. Quantum physics attributes two paths for neutrons inside the the interferometer, which are necessary for explaining the interference. The equations of quantum mechanics tell us that when a neutron reaches a beam splitter, its quantum wave splits into two parts. This is observed in numerous experiments. An experimentalist can tune the interferometer described in Fig. 1a such that no neutrons reach the detector D_2. Moreover, one of the ways to tune the neutron interferometer is to put a line of charges between the arms. This is the Aharonov-Casher effect [6, 7] the topological character of which leaves no other choice but to accept that the neutron must be in two arms and “experience” different forces in these two arms. To avoid schizophrenic neutrons, the MWI postulates that within a world neutrons cannot have distinct experiences, i.e., that from the moment a neutron enters the interferometer and until leaving it, there are two worlds for the neutron: in one world it takes arm A and in another, arm B.

Bohmian mechanics avoids schizophrenia of the neutron without multiple worlds by adopting one of the experience postulates. In the MWI framework, in the neutron MZI experiment there are two “neutron worlds”, while in the BM there is only one neutron world. However, we cannot state that there is an observational difference. The experiences of the neutron in the BM are identical to those of the neutron in one of the MWI worlds. In the framework of the MWI we do not have direct observational evidence for the existence of multiple worlds, and both worlds of the MWI are possible Bohmian worlds. So there is no neutron passing an MZI, which has evidence for one interpretation and not the other.

Bell [8] was the first to recognize a strange behavior of the Bohmian trajectories in MZI without the second beamsplitter, see Fig. 1c. When the Bohmian particle moving in one arm of the MZI reaches the place O where the second beamsplitter has been, it is “caught” by the empty wave moving in the other arm and changes its velocity without any physical fields in this place. In this experiment, the history of experiences of the neutron in BM is different from any of the histories of experiences in the two neutron worlds of the MWI. The difference is in the BM jump from one MWI world to another. However, the jump and the history of experiences

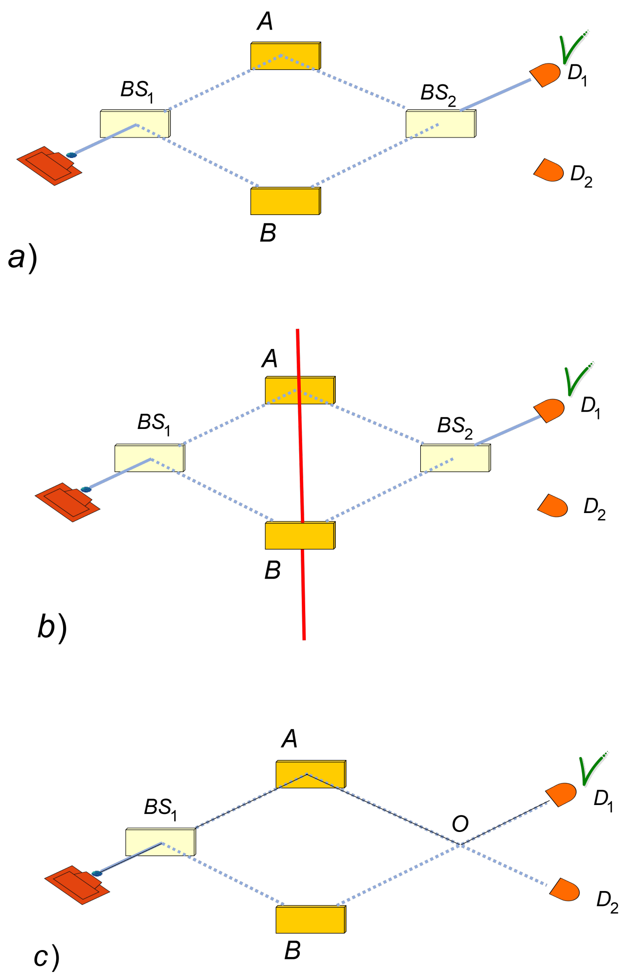

Fig. 1 Schematic picture of neutron Mach-Zehnder interferometer. (In laboratory implementations beamsplitters and mirrors are just parts of cut crystal.) (a) Neutron interferometer tuned to destructive interference toward detector D_2. (b) Aharonov-Casher effect. The phase of the neutron interferometer is tuned by changing the charge density of the line of charges passing through the interferometer. (c) Bohmian trajectory (continuous black line) in the interferometer without second beam splitter

are not "written" in the memory of the neutron, so there is no moment of time in which the neutron can distinguish between the BM and the MWI. Indeed, although it is suggestive to assume that the neutron has different experiences when it accelerates, bouncing off a mirror or jumping from one wave packet to another at point O, the physicalism requires that the experience of a sentient being is given by a model of her brain (or the central processing unit). If the neutron does not have an internal structure, it cannot have experiences, while adding an internal structure of the neutron complicates the experiments. Indeed, a neutron, having memories of different experiences in arms A and B, will not interfere in the output ports of the MZI and we will not see the Aharonov-Casher effect. However, the interference was important when we argued for the necessity of the MWI but not for the question of observational differences between the MWI and the BM.

Consider a natural model of the neutron experience, its spin. (In BM this model requires accepting supervenience postulate II, i.e. that experience supervenes on the Bohmian collapsed spin wave function.) Let us put a magnetic field on path B which flips the spin of the neutron, and thus the spin will provide a memory of the experience in different arms. Adding interacting spin spoils the interference of the MZI, but does not change the behavior of Bohmian particles as described in Fig. 1c. The Bohmian particle still jumps to the empty wave accelerating in a place without fields. The MWI world and the BM worlds have different histories, but again, there is no moment of time when the neutron, within a world, has evidence of the difference between BM and the MWI.

In order to consider the BM supervenience postulate I, we can replace the neutron by an atom and consider the experience at different paths recorded in different Bohmian positions of the particles the atom consists of. But if the internal quantum states of wavepackets moving on path A and path B differ, the jump of the Bohmian positions to the empty wave packet will not happen, and so the experience in the possible BM worlds will be identical to the experiences in the atom's world of the MWI. If using a supertechnological device we erase the memory in the wave packets of the neutron just before they reach the meeting point O, the histories in the BM world and the worlds of the MWI will be different, but the neutron will not have the memory to verify this. In all cases we do not have any observational difference.

In fact, for analyzing the MWI, even a sentient neutron or atom is a very problematic example because they are not macroscopic. Experience of a sentient being is defined only within a world, since in different worlds sentient beings have different experiences. According to my definition [3]:

> *A world is the totality of macroscopic objects: stars, cities, people, grains of sand, etc. in a definite classically described state.*

Important aspects of the problem cannot be considered with microscopic objects. Adding a microscopic object to the description of a world leads to a very different behavior [9, 10].

4 Wigner's cat

Although there are (few) claims to the contrary, I am not aware of any realistic experiments which can distinguish between different interpretations of quantum mechanics (apart from constraining parameters of some physical collapse theories [11]). But I think it is important to consider the possibility of observational differences in gedanken experiments, which require technology that is not present today and might not even be present in any foreseeable future.

A gedanken experiment that has attracted renewed attention is the Wigner friend [12, 13]. Despite the alleged experimental demonstrations [14] I do not expect that the experiment will be performed in a real laboratory. Wigner was supposed to measure his macroscopic friend in superposition of macroscopically different states. In [14] the "friend" is a photon, so such an experiment is not better than the neutron interference experiment discussed above.

Let us consider Wigner's friend to be his cat. The cat is macroscopic enough and sentient enough, especially since Wigner trained his cat to be an observer in a spin experiment. The cat stands up if the detector corresponding to outcome "up" clicks and lays down if detector "down" clicks. At time $t = 0$ the Stern-Gerlach experiment measuring spin in the z direction of a particle with initial state $|\uparrow_x\rangle$ is performed. The cat observes the result and acts according to her training.

Consider the following set of Wigner measurements. First, immediately after the procedure, he measures the observable of the lab with the cat which has two eigenstates: $|+\rangle$ and $|-\rangle$, where

$$|\pm\rangle \equiv \frac{1}{\sqrt{2}}(|cat\ stands\ up\rangle|\uparrow_z\rangle \pm |cat\ lays\ down\rangle|\downarrow_z\rangle. \tag{1}$$

Then, Wigner keeps the lab isolated and repeats the same measurement (with appropriate changes due to time evolution) every minute.

If the correct theory describing the universe is quantum mechanics with collapses when macroscopic objects are in superposition of macroscopically different states, then the possible results of Wigner are $+,+,-,+,-,...$ This is because states $|+\rangle$ and $|-\rangle$ are superpositions of the cat standing up and laying down, so during the sixty seconds between Wigner's measurements they will collapse either to state $|cat\ stands\ up\rangle$ or to state $|cat\ lays\ down\rangle$ after which there is an equal probability for results "$+$" and "$-$" of Wigner's measurements.

If the correct theory describing the universe is the MWI or BM, then, Wigner's results are deterministic: $+,+,+,+,+,...$ At time $t = 0$ the state $|+\rangle$ is prepared and evolves unitarily to its version at later times. So Wigner (given that he has supertechnology) can distinguish between collapse and non-collapse theories (see also Section 5 of [3]). He cannot distinguish between the BM and the MWI.

The cat can also be considered as an observer. In the framework of the MWI, at every moment there is a cat experiencing standing up and a cat experiencing laying down. In the framework of the BM one of these cats is an empty wave which has no Bohmian positions and does not have any experience. Depending on the way Wigner performs his measurements, in the BM we might have only one type of experience for the cat (say, standing up), or it might change due to the process of Wigner's measurement. (The latter can happen if Wigner performs an interference experiment after bringing the two wave packets of the cat to the same location.) However, Wigner, in order to perform his measurements, has to erase the memory of the cat, so there is no moment in time at which the cat has evidence about what is the right theory, the BM or the MWI.

5 Sentient being with a spin brain

In section 3 we already considered a sentient neutron with a spin brain, but proper analysis requires macroscopic objects. Indeed, in BM one can talk about worlds that differ due to microscopic differences of the Bohmian positions of particles, but in the MWI the concept of a world requires macroscopic differences of macroscopic objects.

Current brain studies do not suggest that our brain works with spin states, but we can imagine a sentient macroscopic robot with brain based on the *macroscopic* number of spin states. A particularly surprising situation will occur if this robot is placed in one arm of the MZI without the second beam splitter to observe the passing neutron there, as in Fig. 1c. Let us consider a world in which the neutron is detected on the detector D_1. Although the robot is macroscopic, if the observation of the neutron changes only its spin states, say flip them from "down" to "up", then from the Bohmian perspective no position measurement has been performed in the arms of the interferometer and, therefore, when the full and empty wave packets of the neutron meet at location O, the Bohmian particle has to jump from one wave packet to another. Therefore, the neutron (detected by D_1) had a Bohmian trajectory along the path A. We get records of the robot telling us that the neutron took the lower path B, while the Bohmian trajectory of the neutron is the upper path A. This situation is named a surrealistic trajectory [15].

In fact, in this setup we can place more robots with spin brains, see Fig. 2 which will all agree after the click of the detector D_1, that the neutron passed through arm B. This does not fit the BM supervenience postulate I, according to which experience supervene solely on Bohmian positions, while here it is the spin states of the brains which "know" the result. We should say that the robots have no experience of seeing the neutron. If we accept the BM supervenience postulate II, we should say that the robots have experience of seeing the neutron in arm B, but they are all mistaken, because the Bohmian trajectory of the neutron was in path A, see Fig. 2c. This is also where the BM collapsed wave of the neutron *was* in the past. Indeed, when the neutron was inside the interferometer, the collapsed wave functions of the robot brains were different, they corresponded to the neutron passing through A, see Fig. 2b. The records of the brains changed to a neutron passing through B when the neutron passed point O, see Fig. 2c.

In my view, the change of brain records is a weakness of the interpretation, but it is not something that has observable consequences. At every moment in time the spin-brain records in BM corresponded to the records in one of the worlds of the MWI, so at no moment in time had the robot any evidence for one interpretation against the other.

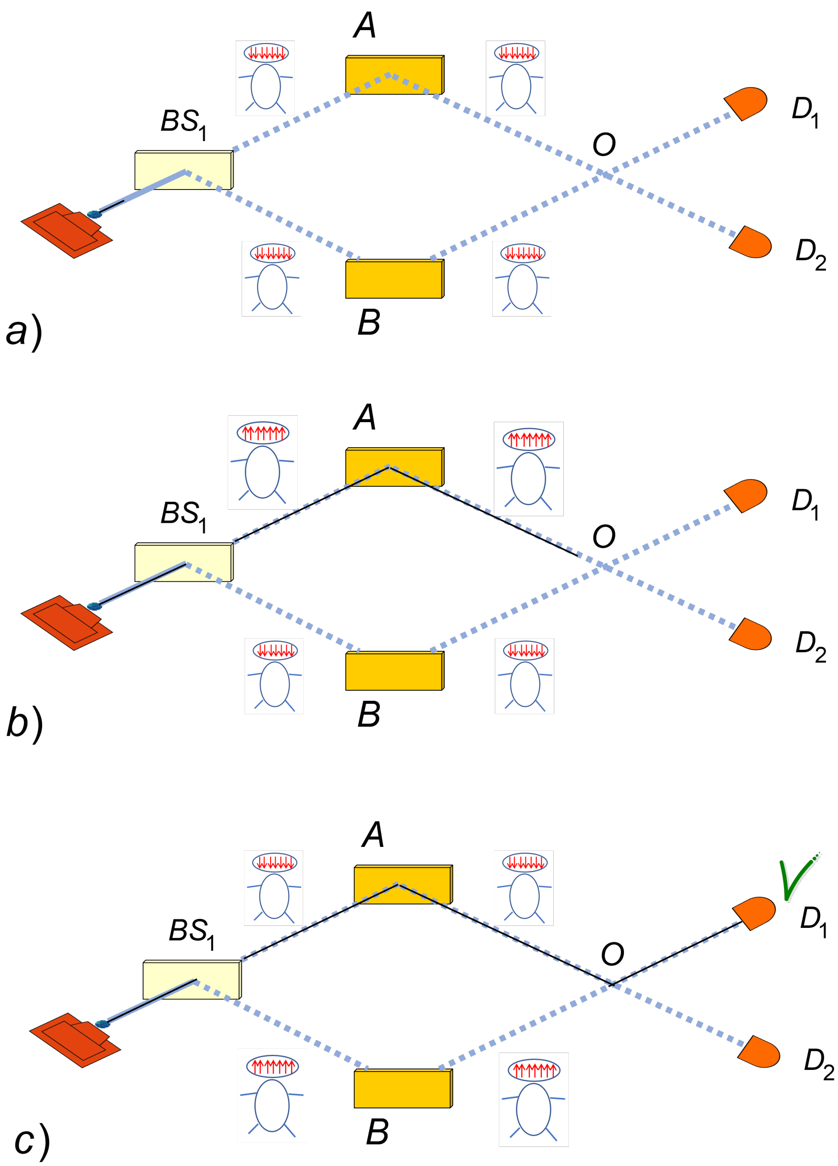

Fig. 2 Surrealistic trajectories of the neutron observed by sentient robots with spin brains. Analysis of the experience of robots according to the BM supervenience postulate II. (a) The neutron enters the MZI interferometer without the second beamsplitter, and sentient spin-brain robots are ready to observe its trajectory. (b) The neutron is inside the interferometer close to the point O. The robots on path A detected the passing neutron (their spin-brain states flipped), while the robots on path B remained in the ready state. (c) The neutron passed the point O and detected by a (standard, Bohmian-pointer) detector D_1. At the moment that the neutron passed the point O, the spin brain memories of the robots on the path A were erased and returned to "ready" while the spin brain states of the robots on the path B changed to (mistaken) records of the neutron passing there.

6 Summary

If we accept the starting point of BM that in the end of the day all quantum measurements are measurements of position of the pointers of the measuring devices (this approach leads to experience postulate I), then the theorem of BM about the robustness of the Born distribution of Bohmian positions under unitary evolution tells us that there cannot be an observational evidence distinguishing BM from the MWI. Ingenious proposals leading to surrealsitic trajectories of the type described above can also be constructed without spins. Surrealistic trajectories appear when local interaction leads to a change in the quantum state (such as acquiring momentum) without an immediate significant change in Bohmian positions [16]. The general statement is that slow measuring devices, i.e. devices with good Bohmian position pointers but which show the results after the empty and the full wave packets pass the intersection point, provide wrong records of Bohmian positions of the particles. It might be slightly disturbing that only Bohmians would claim that such devices are not good measuring devices of position (in all other interpretations, which have no surrealistic trajectories, the measuring devices show correct histories), but no observational differences appear, only different interpretations.

Super technology, a la Wigner, cannot help. The basic supertechnology experiment which allows distinguishing collapse and non-collapse interpretations involves interference between different worlds of the MWI, e.g. an interferometeric device like an MZI, but with macroscopic objects (sentient observers) instead of particles, does not distinguish between BM and the MWI. The MZI without a second beam splitter (the basis of surrealistic trajectories experiments) is simpler than a MZI. It is conceptually different from the interference experiment since there is no interference between the *A* and *B* branches. However, when the branches involve macroscopically different sentient beings, the technology for obtaining surrealistic trajectories is not simpler. Wigner needs to make the two branches identical in the spatial configuration space and then bring them back to their different macroscopic states. All these complicated manipulations will lead to histories in Bohmian mechanics different from those of the MWI, but these scenarios must involve memory erasure of the histories, so at no moment of time will Wigner, or any sentient being he makes the experiment with, have any evidence distinguishing one interpretation from the other.

The existence of sentient beings with spin brains does not change the conclusions. The BM superveninece postulate I does not allow such sentient beings. So, they will know, if they actually exist, that BM with postulate I is incorrect. They will have the option to accept BM with postulate II or MWI. If they will observe particles in experiment like in Fig. 2 (which, in fact, does not require supertechnology, the only gedanken part here is the existence of sentient being with spin brains) the histories of their experiences in the BM framework will be different from those of the MWI, but at no time will there be any evidence for a sentient being about the difference between BM with postulate II and the MWI.

I favor the MWI not because, but in spite of the plurality of worlds, so my motivation for BM is that it singles out one of the worlds of the MWI. I find the BM experience postulate I simple and natural and (in spite of featuring action at a distance) I find that the BM with postulate I is an attractive proposal. However, such a theory has to include at least implicitly a statement of nonexistence of sentient beings with spin brains or any other nonspatial degrees-of-freedom brains.

The alternative, BM with supervenience postulate II, seems less attractive. If experience supervenes on the wave function (the BM collapsed wave function), why not consider the MWI with essentially the same supervenience postulate? One might consider it as an advantage of BM that the BM collapsed wave function is better defined than the MWI branch wave function, but the MWI proponent can say that experience is not something that has to be precisely defined mathematically. Note also that even the BM collapsed wave function is rigorously defined only when the wave function is a superposition of spatially separated wave packets.

The research program of Detlef Dürr was not finished. We do not have a consensus about the interpretation of quantum mechanics. I believe that in my contribution I succeeded to shed some light on similarities and differences of BM and MWI and pointed to the direction which might lead to a progress: understanding better the connection between the formalism of quantum mechanics and our experience.

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