AB29119

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Submission date: 13-Jan-2021 03:57PM (UTC+0000)
Submission ID: 141950078
File name: AB29119_4618138_1729180830.pdf (197.73K)
Word count: 3384
Character count: 18018

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Module Title:	Philosophy of Physics 2
Module Code: (e.g. 5AABC123)	6AANB054

Assignment: (may be abbreviated)	Summative Essay
Assignment tutor/group:	Alexander Franklin
Deadline:	13/01/2021
Date Submitted:	13/01/2021
Word Count:	2728

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How satisfactory is the de Broglie-Bohm theory as a resolution of the measurement problem?

Since its inception, quantum mechanics has been plagued by conceptual difficulties. Despite its extraordinary predictive capabilities and striking agreement with experimental results, it is unclear what the theory really describes. Radically different interpretations exist, all competing to be the truest description of reality. Common to all competing interpretations is that they attempt to solve the measurement problem, which lies at the core of the conceptual difficulties in quantum mechanics. In this essay I will consider one such interpretation - the de Broglie-Bohm theory, also known as Bohmian mechanics – and discuss how satisfactory it is as a resolution to the measurement problem.

What must first be answered is whether or not Bohmian mechanics actually solves the measurement problem. I argue that it does, as the wave function in Bohmian mechanics always evolves in accordance with the Schrodinger equation and therefore never collapses. Following this conclusion is a discussion of what cost this resolution comes at. I discuss the problem of reconciling Bohmian mechanics with relativity, the problem of the theory being explicitly non-local and contextual, and the problem of the theory violating the action-reaction principle. I argue that reconciling quantum theory with relativity is a problem for the entire field, not just Bohmian mechanics, that non-locality has experimental evidence for being the true nature of reality, and that contextuality can be given a coherent picture by allowing all other observables to be reduced to the position observable. I conclude that the biggest obstacle hindering Bohmian mechanics from being a fully satisfactory resolution to the measurement problem is the apparent violation of the action-reaction principle and the unclear role of the wave function that causes it.

The Measurement Problem

First, we must discuss what the measurement problem is. As the name suggests, the problem concerns itself with what happens when measurements are made. Famously, measurements in quantum mechanics seem to somehow dramatically change the systems they measure – Schrodinger's cat is both alive and dead until measured/observed, and particles passing through double slits change their behaviour based on whether or not there is a detector present in one of the slits. The textbook description of these famous conundrums is that they are due to there being two conflicting rules of time-evolution in quantum mechanics:

1. The first way a system can evolve in time is by the Schrodinger equation. Evolution of this kind is linear, continuous, and deterministic. Given a set of initial conditions, the Schrodinger equation will predict exactly how the state of the system evolves in time. States can be added together to become a superposition of states – such as being alive or dead at the same time or going through two different slits at the same time.
2. The second way a system can evolve in time is by wave function collapse. The wave function is what describes the state of a system. It is what the Schrodinger equation takes as an input, and which therefore evolves linearly, continuously, and deterministically into superpositions of states. However, when a wave function collapses this superposition of states is reduced to a single state – the cat goes from being dead and alive to being just either dead or alive. Furthermore, it is impossible to predict exactly what state the wave function will reduce to. One can only say something about the probabilities regarding how the wave function will collapse.

In terms of these two rules, the measurement problem can be expressed as the problem of reconciling these two rules – figuring out when each rule applies, and how the transition between the rules occurs. A typical picture given, like the explanation offered by von Neumann in 1932[1], is that the Schrodinger equation governs the motion of a system when it is not being measured, and wave function collapse happens once the system is measured. After collapse, the system is again governed by the Schrodinger equation. However, the problem with this picture is that there is no clear idea of what constitutes a measurement, or how such a measurement is able to affect the system it measures. What is really happening when opening the box with Schrodinger's cat inside, or when placing a detector in a double slit experiment? This is what any interpretation of quantum mechanics must attempt to resolve.

The Wave Function in Bohmian Mechanics

As previously discussed, the wave function can be regarded as a description of the state of a system. However, exactly how to interpret the wave function is a key conceptual difference between the various interpretations of quantum mechanics. In the Copenhagen interpretation, which really includes a whole spectrum of ideas, the wave function is normally taken to be a purely mathematical tool which can only tell us about properties of a system. On the other hand, in many-worlds

[1] von Neumann, J., 1932 [1996]. *Mathematical Foundations of Quantum Mechanics*, R.T. Beyer (trans.), Princeton: Princeton University Press.

interpretations there is a universal wave function, as introduced by Hugh Everett in his 1956 PhD thesis[2], which is an objectively real thing and contains a complete description of the state of any system.

In Bohmian mechanics, the role of wavefunction can be seen as something in between the Copenhagen interpretation and many-worlds. The theory, which was first suggested by Louis de Broglie (1930) and later developed by David Bohm (1952), also considers the wave function to be a real physical thing. However, the wave function does not constitute a complete description of a state in Bohmian mechanics. Instead, the tuple (Ψ, Q) where Ψ is the wave function and Q records the position of the system's particles, provides the complete description. The dynamical system described by (Ψ, Q) is governed by the guidance equation. This is a first order differential equation relating the velocity of a particle to its wavefunction. The guidance equation can be thought of as telling the particle what velocity to have at every point in its time-evolution, guiding it along like a pilot – which is why the theory is also known as the pilot wave theory.

The guidance equation of a system exerts its influence on the particles in a system instantaneously based on the system's configuration and wave function. This means that the theory is explicitly non-local. While the guidance equation, and therefore the wave function, acts on particles it is not affected back by them. The resulting picture Bohmian mechanics paints of e.g. the double slit experiment is that the particle does not somehow go through both slits simultaneously. Instead, it only goes through one slit and has a definite trajectory throughout, like we are used to in classical mechanics. This trajectory is mapped out by the wave function through the guidance equation. The wave function in turn is purely governed the Schrodinger equation. This means that the wave function does develop into a superposition of states in the double slit experiment – important however, the trajectory of the particle does not, and is instead determined by the configuration of the system.

This allows for an intuitive and pleasing picture of quantum mechanics. The cat is always either alive or dead, and particle positions are always determinate. Instead of having measurement outcomes depend on the probabilities in wave function amplitudes, the outcomes are instead predetermined and only *seem* probabilistic because we do not know the full details of the configuration of the system in question. What is more is that the measurement problem is solved! Previously I expressed the measurement problem as the conflict between Schrodinger's equation and wave function collapse in

[2] Bryce Seligman DeWitt, R. Neill Graham, (1973). *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, Princeton University Press, Contains Everett's thesis: *The Theory of the Universal Wave Function*, pp 3–140.

the time-evolution of the wave function. However, in Bohmian mechanics the wave function always follows Schrodinger's equation and never collapses! The problem is therefore entirely avoided.

It should be stressed that predictions in Bohmian mechanics match those of experiment and standard quantum theory. Again, take the case of the double slit – the guidance equation will guide the particles to form the same interference patters experiments show, following the familiar wave function amplitudes. However, the difference is that particles themselves do not experience interference in Bohmian mechanics. The wave function interferes, and the guidance equation guides particles to the appropriate positions based on this wave function and the configuration of the system positions. Throughout the process, particle positions are determinate, most quantum weirdness is eliminated, and the measurement problem is solved – this sounds very promising. The question is then at what cost has this come?

Problems

The first problem that often comes up in the context of Bohmian mechanics is that it is hard to render the theory relativistically invariant since the dynamics of the system – the guidance equation – is of first order as opposed to second order like we are used to in classical mechanics. However, the reconciliation of quantum mechanics and relativity is perhaps biggest challenge in all of contemporary physics today. In fact, the Schrodinger equation that standard quantum theory and Bohmian mechanics builds on is non-relativistic itself. Therefore, since standard quantum theory already is incompatible with relativity, I argue that Bohmian mechanics' resolution to the measurement problem does not come at any cost in this respect. It only highlights that there is still work to be done in this area of Bohmian mechanics and quantum mechanics in general. Dürr, Goldstein, Norsen, Struyve and Zanghi are among the groups tackling this problem in Bohmian mechanics.[3]

Other objections to Bohmian mechanics can be made by appealing to the no-go theorems of Bell's theorem and the Kochen-Specker theorem. However, none of these objections disprove Bohmian mechanics. Instead, they point to some important features of the theory. Bell's theorem[4] proves that quantum physics is incompatible with local hidden-variable theories. We have already seen that Bohmian mechanics is non-local since a particle's velocity is directly affected by the wavefunction

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[3] Dürr Detlef, Goldstein Sheldon, Norsen Travis, Struyve Ward and Zanghì Nino (2014). *Can Bohmian mechanics be made relativistic?* Proc. R. Soc. A.47020130699 DOI: 10.1098/rspa.2013.0699

[4] Bell, J. S. (1964). *On the Einstein Podolsky Rosen Paradox*. Physics Physique Физика. 1 (3): 195–200. doi:10.1103/PhysicsPhysiqueFizika.1.195.

through the guidance equation, which depends on the particle positions (configuration) of the entire system at any time. Further, it is classified as a hidden-variable theory since the wave function does not provide a complete description of the state. The "hidden variable" that completes the picture is particle position. Bohmian mechanics is therefore compatible with Bell's theorem.

One could question how satisfactory Bohmian mechanics is since it allows for non-locality. However, while unintuitive, it is a feature of quantum mechanics that we do have experimental evidence for. It has been tested under different physical assumptions, for example in 2015 by Shalm, LK, et al[5], and Bell himself had this to say on the matter: *[…] nonlocality has turned out to be a fact of nature: nonlocality must be a feature of any physical theory accounting for the observed violations of Bell's inequality […].*[6] Given the experimental evidence, it seems then that non-locality is a feature of nature rather than a peculiarity of Bohmian mechanics – no matter how unintuitive it seems.

While Bell's theorem establishes that hidden-variable theories are non-local, the Kocken-Specker theorem[7] establishes that such theories must also be contextual. In the case of Bohmian mechanics, this means that many of the orthodox observables in quantum mechanics, such as spin and polarization, cannot be said to be pre-existing properties of particles. For example, the outcome of a spin measurement on a particle will depend on the configuration of the setup, and therefore in a sense produce a spin property as opposed to revealing one – in other words, the spin depends on the context. For many, this is a too dramatic departure from classical physics.

However, importantly, position is not contextual in Bohmian mechanics – it is always determinate and does not depend on how you measure it. The Bohmian can therefore respond that position is the only basic observable, and that all other traditional observables can be reduced to it. This involves thinking about observables such as spin in a new way. For example, the traditional thought is that spin is a property that makes an electron deflect up or down in a Stern-Gerlach experiment. However, the Bohmian can instead say that spin is really something that depends on the configuration (orientiation) of the Stern-Gerlach experiment, which then affects the wave function of the system, which through the guidance equation makes the electron deflect up or down. Spin is then not a pre-existing property

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[5] Shalm, LK, et al. (December 2015). *Strong Loophole-Free Test of Local Realism*, Physical Review Letters. 115 (25): 250402. doi:10.1103/PhysRevLett.115.250402

[6] Bell, J. S. (1987). *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, Cambridge, UK.

[7] S. Kochen; E. P. Specker (1967). *The problem of hidden variables in quantum mechanics*, Journal of Mathematics and Mechanics. 17 (1): 59–87. doi:10.1512/iumj.1968.17.17004

of the electron. I argue this is a coherent explanation which allows Bohmian mechanics to be compatible with the Kocken-Specker theorem and deal with contextuality in a neat way.

The final objection I will consider against Bohmian mechanics is one based on the action reaction principle. As previously discussed, the wavefunction in Bohmian mechanics is normally taken to somehow be a *real* object. This is because the wave function, through the guidance equation, directly affects the motion of particles. However, the particles themselves are fundamentally unable to affect the wave function back. This has been pointed out by many, among others Anandan and Brown (1995)[8], as a violation of the action-reaction principle and a serious fault in the ontology of Bohmian mechanics. The action-reaction principle is simply the principle that a physical object cannot act on another physical object without being acted on back – a central concept to all of modern physics, both classical and quantum. I argue that Bohmian mechanics' violation of this principle is the most important problem preventing Bohmian mechanics from being an entirely satisfactory resolution to the measurement problem.

As previously discussed, problems with relativity can be forgiven since this is something the field at large has yet to solve. Non-locality has experimental evidence to support it and nothing preventing it from being true except for our intuition. Similarly, contextuality at first seems unintuitive but can be given a coherent explanation. The problem of violating the action-reaction principle is a different story. This is a new problem that Bohmian mechanics has introduced, and which is not problematic in standard quantum theory or in other quantum interpretations. Solving the measurement problem by unsolving another is not very satisfactory. The root of the problem is the unclear role and ontology of the wave function. If it is real, what kind of physical structure does it represent? Must some new type of physical structure be defined that is allowed to violate the action-reaction principle?

In my view, the most promising resolution of this problem is the one advocated by Dürr, Goldstein and Zanghi in their 1995 paper on the meaning of the wave function.[9] Here, they propose viewing the wave function as a law rather than a physical structure. They do this by showing how the wave function of the universe can turn out to be both unique and time-independent, thereby making it appropriate to regard it as a physical law – analogous to the Hamiltonian in classical mechanics. It is important to

[8]Anandan, J. and Brown, H. (1995). *On the reality of space-time geometry and the wavefunction*, Foundations of Physics 25(2), 349–360.

[9] Durr, D. & Goldstein, Sheldon. (1996). *Bohmian Mechanics and the Meaning of the Wave Function.*

emphasize that this is an ongoing research program and it is too early to say something definite about the results of this approach.

In conclusion, there is still much work to be done in Bohmian mechanics – most importantly in attempting to reconcile it with relativity and to clarify the role of the wave function. However, it provides an elegant resolution to the measurement problem, staying unaffected by the no-go theorems. The most important factor, I argue, keeping Bohmian mechanics from being an entirely satisfactory resolution to the measurement problem is the unclear role played by the wave function – a problem that other interpretations of quantum physics are able to avoid.

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GRADEMARK REPORT

FINAL GRADE

/100

GENERAL COMMENTS

Provisional mark: 68

This is a clear well written essay that sets out the issues well. There is evidence of appropriate reading and a good understanding of the subject matter. The argument is largely convincing but note that relativistic quantum mechanics is well developed - it leads to quantum field theory and the physics of the standard model.

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