Bohmian Mechanics and the Measurement Problem

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Abstract

The measurement problem in quantum mechanics is a fundamental issue that has puzzled physicists for decades. Bohmian Mechanics, a non-local hidden variable theory, offers a potential solution by providing a deterministic framework. This paper is about how Bohmian Mechanics addresses and resolves the measurement problem.

1 Introduction

The measurement problem is a long-standing problem of quantum mechanics and amounts more or less to the paradox of Schrödinger's cat. When assuming the wave function is a complete description of the system, the linear dynamics is apparently incompatible with the appearance of definite results of measurements on the system. This leads to the measurement problem.

In order to solve the measurement problem (in a way different from the many-world interpretation), Bohmian mechanics assumes that the result of a measuring device is determined not by the branch of the post-measurement wave function in which its Bohmian particles reside, but by the configuration of its Bohmian particles.

In this paper, we discuss what exactly the measurement problem is, the arguments prevalent related to it and historical considerations and finally we analyse and provide a stance on how Bohmian Mechanics solve this problem.

2 The Measurement Problem

In quantum mechanics, the measurement problem is the problem of definite outcomes: quantum systems have superpositions but quantum measurements only give one definite result.

Suppose that the wave function of any individual system provides a complete description of that system. When we analyze the process of measurement in quantum mechanical terms, we find that the after-measurement wave function for system and apparatus that arises from Schrödinger's equation for the composite system typically involves a superposition over terms corresponding to what we would like to regard as the various possible results of the measurement e.g., different pointer orientations. In this description of the after-measurement situation it is difficult to discern the actual result of the measurement e.g., some specific pointer orientation. But the whole point of quantum theory, and the reason we should believe in it, is that it is supposed to provide a compelling, or at least an efficient, account of our observations, that is, of the outcomes of measurements. How then is it possible to account for the fact that superposition states are never actually observed? According to the standard interpretation of quantum mechanics, when a physical system is being observed, a second category of explicitly probabilistic laws applies exclusively. These laws do not determine a precise position for a given particle but determine only a probability that it will have one position or another.

In short, the measurement problem is this: Quantum theory implies that measurements typically fail to have outcomes of the sort the theory was created to explain.

3 Approaches to solve this theory

- Copenhagen interpretation are the oldest and, collectively, probably still the most widely held attitude about quantum mechanics, stemming from the work of Niels Bohr, Werner Heisenberg, Max Born, and others. Copenhagen tradition posit something in the act of observation which results in the collapse of the wave function.

- Hugh Everett's many-worlds interpretation attempts to solve the problem by suggesting that there is only one wave function, the superposition of the entire universe, and it never collapses—so there is no measurement problem. However, proponents of the Everettian program have not yet reached a consensus regarding the correct way to justify the use of the Born rule to calculate probabilities.

- The third approach is given by objective-collapse models. The 'Objective collapse model' theory proposes that the wave function spontaneously 'jumps' from possibilities to a single reality, even without an observer. These models aim to remove the need for an observer causing the collapse and offer a more objective view of how the quantum world becomes the classical world known to us.

- The theory of Ghirardi, Rimini, and Weber affirms that wave functions are complete representations of physical systems but denies that they are always governed by the linear differential equations of motion. The strategy behind this approach is to alter the equations of motion so as to guarantee that the kind of superposition that figures in the measurement problem does not arise.

- The theory of Bohm

4 Bohm's theory

Bohm's theory is an interpretation of quantum mechanics developed by physicist David Bohm. The theory gives us a new interpretation of describing particles at the quantum level and differs from the traditional description offered by quantum mechanics. In Bohmian mechanics, particles are described as having specific positions and trajectories, in contrast to the probabilistic nature of particle behavior in standard quantum mechanics. This determinism is achieved by introducing a guiding wave, known as a pilot wave, which affects the motion of the particles. The pilot wave guides the particles in such a way that their collective behavior is consistent with the statistical predictions of standard quantum mechanics. Bohm postulated that, instead, the wave function was the De Broglie matter wave associated to the particle, and that the wave-particle duality was composed of the matter wave and the particle as distinct entities. Moreover, the behaviour of the particle is dictated by the matter wave (or wave function) associated to it. The matter wave takes a certain shape depending on the potentials it is subject to (accounted for in the Schrödinger equation) and this way it guides the particle on a certain trajectory. For small time intervals, Bohmian trajectories may seem similar to Brownian motion or chaotic behaviour. But for larger time intervals, patterns arise which show the large-scale interference patterns the matter wave creates by interacting with the potential fields in the environment of the particle.

5 Schrödinger's equation

The one-particle Schrödinger equation governs the time evolution of a complex-valued wavefunction . The equation represents a quantized version of the total energy of a classical system evolving under a real-valued potential function V on R^3 :

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi$$

For many particles, the equation is the same except that Ψ and V are now on configuration space. This is the same wavefunction as in conventional quantum mechanics.

$$i\hbar\frac{\partial\Psi}{\partial t} = -\sum_{k=1}^{N}\frac{\hbar^2}{2m_k}\nabla_k^2\Psi + V\Psi$$

6 Guiding equation

For a spinless single particle moving in R^3,

the particle's velocity is given by:

$$\frac{dQ}{dt}(t) = \frac{h}{m}\mathrm{Im}\left(\frac{\nabla\Psi}{\Psi}\right)(Q,t)$$

For many particles, we label them as Qk for the K-th particle, and their velocities are given by:

$$\frac{dQ}{dt}(t) = \frac{h}{m_k}\mathrm{Im}\left(\frac{\nabla_k\Psi}{\Psi}\right)(Q_1, Q_2, ..., Q_n)$$

7 How Bohmian mechanics solve the measurement problem

Bohm's approach stipulates that a physical particle is the sort of thing that is always located in one particular place or another. In addition, wave functions are not merely mathematical objects but physical ones—physical things. Somewhat like force fields (electric fields or magnetic fields) in classical mechanics, they serve to push particles around or to guide them along their proper courses.

Thus, the positions of all of the particles in the world at any time, and the world's complete quantum mechanical wave function at that time, can in principle be calculated with certainty from the positions of all of the particles in the world and the world's complete quantum mechanical wave function at any earlier time.

Suppose that a single electron with x-spin = +1 is fed into the apparatus. On Bohm's theory, the electron will take either the y = +1 path or the y = 1 path—period. Which path it takes will be fully determined by its initial wave function and its initial position (though certain details of those conditions will be impossible in principle to ascertain by measurement). No matter what route the electron takes, however, its wave function, in accordance with the linear differential equations of motion, will split up and take both paths. In the event that the electron takes the y = +1 path, it will be reunited at the black box with that part of its wave function that took the y = 1 path.

One of the consequences of the laws of Bohm's theory is that, at any given time, only that part of a given particle's wave function that is occupied by the particle itself at that time can have any effect on the motions of other particles. Thus, any attempt to detect the "empty" part of a wave function that is passing through one of the two paths will fail, since the detecting device itself consists of particles. This accounts for the absence of superposition in actual measurements of electrons emerging from the y-box.

Collapse of the universal wavefunction never occurs in de Broglie–Bohm theory. Its entire evolution is governed by Schrödinger's equation, and the particles' evolutions are governed by the guiding equation.

The reason Bohmian Mechanics is said to solve the measurement problem is that the outcome of the time-evolution, interpreted suitably, is a detector eigenstate. In Bohmian Mechanics, one has a distribution of particles but interprets the actual ontic state of the system to be only one of them. Loosely speaking, Bohmian Mechanics combines the Schrödinger evolution and the Collapse Postulate to one local evolution for the particle and a non-local one for the guiding field. Since by assumption there is only one particle in the initial distribution, there is only one final outcome.

The de Broglie–Bohm theory tries to solve the measurement problem very differently: the information describing the system contains not only the wave function, but also supplementary data (a trajectory) giving the position of the particle(s). The role of the wave function is to generate the velocity field for the particles. These velocities are such that the probability distribution for the particle remains consistent with the predictions of the orthodox quantum mechanics. According to de Broglie–Bohm theory, interaction with the environment during a measurement procedure separates the wave packets in configuration space, which is where apparent wave function collapse comes from, even though there is no actual collapse.

8 Limitations of Bohm's theory

Bohmian mechanics, while offering a potential solution to the measurement problem, isn't universally accepted and has its share of criticisms.

- Non-Locality: One of the biggest challenges is the non-local nature of the guiding wavefunction. It suggests instantaneous correlations between distant particles, which violates the principle of locality in relativity.

- Hidden Variables: The theory introduces hidden variables, which are additional properties beyond the wavefunction. These haven't been experimentally observed, and some physicists argue for simpler explanations without them.

- Occam's Razor: This principle favors simpler explanations. Bohmian mechanics adds complexity with the guiding wavefunction, which some view as unnecessary since the standard interpretation produces the same statistical predictions.

- Compatibility Issues: Integrating Bohmian mechanics with special relativity (a fundamental theory of physics) has proven challenging.

Contrary to the received view, when assuming that (1) quantum entanglement plays no role in our brain in forming our conscious perceptions and (2) a system whose elements have no causal connections does not have conscious minds, Bohmian mechanics fails to provide an explanation of our determinate conscious perception of the measurement result.

9 Conclusion

It has been realized that the measurement problem is essentially the determinate experience problem. The problem is not only to explain how the linear dynamics can be compatible with the appearance of definite measurement results obtained by physical devices, but also, and more importantly, to explain how the linear dynamics can be compatible with the existence of definite experiences of conscious observers.

In Bohm's theory, measurement is a dynamical and essentially a many-body process.There is no collapse of the wavefunction and, hence, no measurement problem. The basic idea is that a particle always has a definite position between measurements. There is no superposition of properties and "measurement" (or observation) is an attempt to discover this position.

In this paper we have discussed about how Bohmian mechanics solve the measurement problem. For that we have also given an overview of the measurement problem and all the theories that surround it in the solving the same like Hugh Everett's many-worlds interpretation, objective collapse models, etc. Along with that we have discussed about Bohm's theory in general and then in particular related to measurement problem and collapse in wave function.

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