The epistemic view of quantum states and the ether

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Abstract

The idea that the wave function represents information, or knowledge, rather than the state of a microscopic object has been held to solve foundational problems of quantum mechanics. Realist interpretation schemes, like Bohmian trajectories, have been compared to the ether in pre-relativistic theories. I argue that the comparison is inadequate, and that the epistemic view of quantum states begs the question of interpretation.

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1 Introduction

For the past twenty years, quantum information theory has been one of the most rapidly developing areas of quantum mechanics [1]. Teleportation of unknown quantum states over large distances has been reported, and practical implementations of quantum cryptography are already available. Although large-scale quantum computers may not be coming soon, work in that direction is likely to throw much light on the fundamental process of decoherence and perhaps on the limits of quantum mechanics itself.

Investigations in the foundations of quantum mechanics have significantly contributed to the development of quantum information theory. A number
of people believe that in turn, quantum information theory has much to contribute to the understanding and interpretation of quantum mechanics. This has to do with what is often called the epistemic view of quantum states, which goes back at least to Heisenberg but has significantly evolved in the past few years [2 3 4]. The basic assertion of the epistemic view is that the wave function (or state vector, or density matrix) represents knowledge, or information. On what the wave function is knowledge of, proponents of the epistemic view do not necessarily agree. The variant most relevant to the present discussion is that rather than referring to objective properties of microscopic objects (such as electrons, photons, etc.), the wave function encapsulates probabilities of results of eventual macroscopic measurements.

The proponents of the epistemic view believe that it considerably attenuates, or even completely solves, the notorious problems of quantum measurement and long-distance correlations. Briefly, if the wave function is interpreted as referring to the objective state of a physical system, its collapse in a quantum measurement involves a physical process that calls for explanation. If, however, the wave function simply represents knowledge of the probabilities of results, its abrupt change points to a change of knowledge, rather than to a physical change in some microscopic system. In a similar way, the epistemic view helps removing the clash between collapse and Lorentz invariance. In the EPR setup, for instance, Alice’s measurement of her photon’s spin does not instantaneously produce the collapse of the spin wave function of Bob’s photon. Rather it changes Alice’s knowledge of the probabilities of results of spin measurements on Bob’s photon. Bob can of course perform the measurement, but otherwise Alice’s knowledge can only be transferred to him by conventional means.

In the epistemic view, the Hilbert space formalism of quantum mechanics is taken as complete, and its objects in no need of a realistic interpretation. Thus any additional constructs, like value assignments in modal interpretations [5 6], multiple worlds [7], or Bohmian trajectories [8 9 10] are viewed as superfluous at best. Such constructs predict no empirical consequences other than what is already derivable from the Hilbert space formalism. This has lead to comparing them with the ether in classical electrodynamics [11 12 13]. Just as the ether was discarded after special relativity had shown that it led to no specific empirical consequences, so should additional constructs to the Hilbert space be done away with in quantum mechanics.

The purpose of this paper is to investigate whether the roles fulfilled
by the ether in electrodynamics and by realistic interpretation schemes in quantum mechanics are comparable, and whether the epistemic view provides an adequate understanding of quantum states.\footnote{Further thoughts on these questions can be found in Refs. \cite{14} and \cite{15}, on which the present discussion is based.}

\section{Ether and field}

The concept of ether has a long history, and it has been the subject of detailed analyses \cite{16,17}. In one of its many uses, it was viewed as a substratum wherein electric and magnetic phenomena take place. In the nineteenth century, a number of complicated mechanical models were proposed to account for its properties, by such distinguished physicists as J. C. Maxwell and W. Thomson, among others. Although a review of such models would lead us too far astray, it is appropriate to look at the way the ether was seen by H. A. Lorentz, at the turn of the twentieth century.

By that time Lorentz had settled on the concept of a stationary ether introduced by A. J. Fresnel in the first decades of the nineteenth century. Material bodies moving through the ether would leave it undisturbed, except for carrying their own excess ether responsible for such characteristics as their index of refraction. The stationary ether explained very well phenomena like stellar aberration. It was viewed as defining an absolute reference frame, the one in which Maxwell’s equations would hold.

Lorentz’s point of view on electromagnetic theory, “a surprising and audacious step” in the words of Einstein \cite[p. 35]{18}, was much simpler than his predecessors’. For him there is ponderable matter, there are electric charges (“electrons”), and there is the ether, “the receptacle of electromagnetic energy and the vehicle for many and perhaps for all the forces acting on ponderable matter” \cite[p. 30]{19}. Lorentz did not commit himself on whether all matter is made of electric charges, nor on whether all mass has an electromagnetic origin.

As there was no reason to expect that the earth is at rest with respect to the ether, the question arose as to how to describe electromagnetic phenomena in a moving frame. What Lorentz and Poincaré progressively realized was that one can define coordinates associated with the moving frame and linear combinations of the electric and magnetic field components such that these combinations and coordinates satisfy Maxwell’s equations. This was
interpreted as meaning that no electromagnetic (and, in particular, optical) measurements could reveal motion through the ether. Yet Lorentz and Poincaré still appealed to a dynamical deformation of bodies in motion, and retained the notions of absolute rest and absolute time. It was Einstein’s fundamental contribution to see that these notions could be dispensed with, and that all inertial frames were equivalent in all respects.

Einstein could therefore do away with the ether. But the field concept became all the more important. Hitherto dependent on the ether, the field now acquired its full autonomy. It was no longer viewed as in need of a substratum. The rejection of the ether, therefore, did not leave a void in its stead. The ether was discarded as defining absolute time and motion, but its function with respect to electromagnetic phenomena was transferred to the field itself.

3 Bohmian trajectories

Bohm’s approach to quantum mechanics is an example of a realistic interpretation. It can be formulated equally within the context of the Schrödinger or the Dirac equation. We shall look more specifically at the latter.

The Dirac equation for a particle of mass $m$ and charge $e$ in an external electromagnetic field $A^\mu$ is given by

$$-i\gamma_\mu \frac{\partial \psi}{\partial x_\mu} + \frac{e}{\hbar} \gamma_\mu A^\mu \psi + \frac{mc}{\hbar} \psi = 0.$$  

(1)

Eq. (1) implies the existence of a conserved current $j_\mu = \bar{\psi} \gamma_\mu \psi$, where $\bar{\psi} = \psi^\dagger \gamma_0$. Bohmian trajectories can be introduced by specifying that the three-velocity of the particle at the space-time point $(r,t)$ is given by

$$v = c \frac{j}{j_0}.$$  

(2)

It can be shown that the magnitude of the velocity never exceeds $c$, and that if particles are distributed according to the probability density $j_0 = \psi^\dagger \psi$ at a given time and follow the trajectories, they will be distributed according to $\psi^\dagger \psi$ at any other time. Averages computed on an ensemble of Bohmian particles exactly coincide with averages computed by means of the Dirac equation.
Thus Bohmian trajectories make no empirical predictions not already obtainable from standard (Schrödinger or Dirac) quantum mechanics. A similar remark can be made about all realistic interpretations of quantum mechanics that leave its basic formalism intact. Just like the (unobservable) ether was discarded with the advent of special relativity, shouldn’t we do away then with the trajectories or other additional constructs to the Hilbert space structure?

Before examining this question, one more analogy between quantum mechanics and the ether should be pointed out. We have seen that in the usual approach to quantum measurement, the collapse of the wave function is essentially instantaneous. Alice’s measurement of her photon immediately produces the collapse of the wave function of Bob’s. It would then seem that wave function collapse introduces a preferred reference frame. Such a frame also appears to be required in the Bohmian mechanics of many particles [9, 20]. One can show that this does not prevent the construction of a relativistically covariant theory of observables, but it is a strong obstacle to the construction of such a theory of beables [21].

4 Two explanatory roles

Bohmian trajectories and the ether are elements of two different theoretical structures. They present both analogies and differences. The analogy that is relevant here is that neither Bohmian trajectories in quantum mechanics nor the ether in special relativity lead to specific empirical consequences. Does this mean that the trajectories, or other interpretative devices, have in quantum mechanics the same status as the ether in special relativity? And if one can dispense with such devices, is there something which, like the field, plays the role they would otherwise have?

To examine these questions, it is appropriate to start with the following observation. Although all measurements are made by means of macroscopic apparatus, quantum mechanics is used, as an explanatory theory, in two different ways: it is meant to explain (i) nonclassical correlations between macroscopic objects and [ultimately through quantum field theory] (ii) the small-scale structure of macroscopic objects. To show that these two functions are distinct, we will consider a hypothetical situation where only one of them is operating.

Consider a world where objects that are not too small (say, larger than
the wavelength of visible light) behave, for all practical purposes, like similar objects in the real world. Classical mechanics can be used to compute the trajectories of projectiles, and classical hydrodynamics the flow of water in pipes. Antennas and waveguides are described by Maxwell’s equations. Chemical equilibrium and phase transitions obey the laws of classical thermodynamics. All objects in the solar system have trajectories well described by Newton’s laws of gravitation and motion, perhaps slightly corrected by the equations of general relativity.

As we go down to scales much smaller than a fraction of a micron, however, these laws may no longer hold. Except for one restriction soon to be spelled out, I shall not be specific about the changes that macroscopic laws may or may not undergo in the microscopic realm. Matter, for instance, could either be continuous down to the smallest scales, or made of a small number of constituent particles like our atoms. The laws of particles and fields could be the same at all scales, or else they could undergo significant changes as smaller and smaller distances are being probed.

In the hypothetical world, some macroscopic objects at times behave in ways that cannot be explained by the classical theories. There may be, for example, objects like our Geiger counters that click when objects like our radioactive materials are brought nearby. Or there may be instruments like our Stern-Gerlach devices which, when placed in front of an oven and suitable collimators, modify the pattern of blackening on a plate behind. There may even be large objects like some of our particle accelerators, which in appropriate situations produce various tracks in saturated vapour. In all these instances, the probabilities of occurrence of events can be calculated on the basis of the quantum-mechanical rules.

To explain the nonclassical correlations described above between macroscopic objects, one can think of at least two very different conceptual schemes. One can assume the existence of microscopic objects, or “particles,” going from emitters to detectors, ovens to plates or accelerators to vapour, whose properties correspond to operators in the Hilbert spaces used to compute the probabilities. Or one can refrain from postulating such microscopic objects, and assume instead something like genuine fortuitousness \[^{[13, 22]}\], where clicks or “detection events” are essentially uncaused.
5 Only one world

I now make an assumption about the hypothetical world, which characterizes the fundamental way in which it differs from the world we live in. I suppose that the “particles” used in the first explanatory scheme above have nothing to do with the microscopic structure of the macroscopic objects. That is, the ultimate constituents of matter, if any, are completely different from whatever is responsible for the nonclassical correlations. In the hypothetical world, the function of the quantum-mechanical rules is solely to explain these nonclassical correlations. In that case the explanatory schemes of particles and genuine fortuitousness are both adequate to the job.

In the actual world, however, the situation is different. The observables, quantum numbers, and Hilbert spaces relevant to the description of particles responsible for macroscopic correlations are the same as the ones used in describing the microscopic structure of macroscopic objects. Rutherford’s α particles produced by radioactive radon and scattered by thin foils of gold have the quantum numbers of helium nuclei!

How are proponents of the epistemic view going to deal with that? One way is to adopt a strong instrumentalist stance and deny either that microscopic objects exist or have states. Indeed [13, p. 410]

[i]t is a hallmark of the theory based on genuine fortuitousness that it does not admit physical variables. It is, therefore, of a novel kind that does not deal with things (objects in space), or measurements, and may be referred to as the theory of no things.

The view that microscopic objects do not exist or have no states is not logically inconsistent. But it raises the question, How can macroscopic objects exist and have states, and yet be reducible to microscopic objects that either do not exist or do not have states? How can the world be for the formalism of quantum mechanics to be true? That question can in fact be viewed as the fundamental problem of the interpretation of a theory [9]. Interpreting a theory coincides with giving one (or several) ways in which the formalism of the theory can be truly realized. The upshot is that the strong instrumentalist stance that microscopic objects don’t exist or don’t have states does not constitute an interpretation, but asks for one.

Without going so far as denying the existence of microscopic objects or their states, proponents of the epistemic view can claim that their introduction is methodologically inappropriate [11, p. 260].
If $T'$ and $T''$ are empirically equivalent extensions of a theory $T$, and if $T$ entails that, in principle, there could not be evidence favoring one of the rival extensions $T'$ or $T''$, then it is not rational to believe either $T'$ or $T''$.

Here $T$ can stand for the Hilbert space formalism of quantum mechanics, $T'$ for its Bohmian extension, $T''$ for Everett’s worlds, etc. If $T$ is singled out among its empirical equivalents, it must be on the basis of criteria other than empirical, perhaps something like Ockham’s razor. This comes as no surprise since even within the class of internally consistent theories, acceptance almost never depends on empirical criteria alone.

But here $T$ is just not complete. The Hilbert space of quantum mechanics makes contact with experiments by means of ill-defined concepts, like the one of a macroscopic apparatus. We are never told what precise criteria of size, mass or constitution make an aggregate of matter an apparatus. $T'$ and $T''$ may be preferable to $T$ just because they are more complete.

Neither Bohmian trajectories nor the ether lead to specific consequences. There have been suggestions that just as the ether was replaced by the field with the advent of special relativity, additional constructs to the Hilbert space formalism should be discarded and replaced by the emergence of the concept of information.

Just as Einstein’s analysis (based on the assumption that we live in a world in which natural processes are subject to certain constraints specified by the principles of special relativity) shows that we do not need the mechanical structures in Lorentz’s theory (the aether, and the behaviour of electrons in the aether) to explain electromagnetic phenomena, so the CBH analysis (based on the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information) shows that we do not need the mechanical structures in Bohm’s theory (the guiding field, the behaviour of particles in the guiding field) to explain quantum phenomena [11, p. 262].

The CBH analysis referred to is an important result recently obtained by Clifton, Bub, and Halvorson [23, 24]. Working in the setting of $C^*$-algebras, these investigators characterized the quantum theory by three properties:
(i) kinematic independence, i.e. the commutativity of the algebras of observables pertaining to distinct physical systems; (ii) the noncommutativity of an individual system’s algebra of observables; and (iii) nonlocality, i.e. the existence of entangled states for spacelike-separated systems. They then showed that these properties are equivalent to three information-theoretic constraints, namely, the impossibility of superluminal information transfer, of perfect broadcasting, and of unconditionally secure bit commitment.

The concept of information is no doubt relevant to the first explanatory function of quantum mechanics, the one that pertains to nonclassical correlations between macroscopic objects. But it is of no help in accounting for the microscopic structure of macroscopic objects. No proponent of the epistemic view (as far as I know) would go so far as claiming that objects are made of information. This is in sharp contrast with the concept of field which, unlike information, does not need material support and carries energy and momentum of its own. Even in classical electrodynamics, there were proposals that all the mass of charged particles is in fact field energy [25]. The analogy between field and information is defective in an essential way.

6 Conclusion

Neither the ether nor Bohmian trajectories have specific empirical consequences. Special relativity, while rejecting the ether as defining an absolute reference frame, transferred its function of substantive medium to the field itself. Bohmian trajectories, or other interpretative schemes of quantum mechanics, try to make the basic variables of the theory, in terms of which the structure of macroscopic objects is ultimately explained, intelligible. This makes them fundamentally different from the ether, and points to the inadequacy of the epistemic view of quantum states.

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