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BOOK REVIEW

Looking for a quantum ontology

Detlev Dürr and Stefan Teufel: Bohmian mechanics: The physics and mathematics of quantum theory. Springer, 2009, xii+393 pp, €69.95 HB

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Every student or teacher or philosopher of science must at some point have wondered: is there really a problem with quantum mechanics, or is it just that the theory is counterintuitive, the mathematics complicated, the world indeterministic or the textbooks badly written? The unambiguous answer given in this extremely important and well-written book is that there is indeed a genuine problem with ordinary quantum mechanics, but also that there is a solution.

The problem is usually called the measurement problem, but it should rather be called the problem of the meaning of the wave-function. In quantum mechanics, the ‘complete description’ of any system is supposed to be given by its wave-function. But a wave-function is just a vector in an abstract space and it is not at all clear what that sentence means. To explain the problem, consider first classical mechanics. In this theory, the notion of ‘force’ (acting instantaneously throughout the universe) is also obscure. Nevertheless, there are particles in the universe, on which the forces act—which determines their motion. Similarly, in classical electromagnetism, the notion of waves propagating in vacuum is obscure, but again, the waves act on particles and guide their motion. Similar remarks hold for the curved space–time of General Relativity. In all those theories, there is an *ontology*, to use the expression of Dürr and Teufel, namely something that exists independently of any human observation or even independently of the existence of mankind itself and whose evolution is described by the laws of physics.

There is nothing of the sort in ordinary quantum mechanics. Indeed, in the latter, the abstract vector called the wave-function has no meaning whatsoever, except that it enters into an algorithm that predicts (very accurately) ‘results of measurements’. There is no ontology in ordinary quantum mechanics—there is nothing ‘out there’ that the theory speaks about. Note that this problem has nothing to do with the issue

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of determinism: one could very well imagine a physical theory whose most fundamental equations are stochastic; it would still be a physical theory about something (particles, waves, whatever). The problem does not come from realism either, at least not as it is usually meant philosophically. In ordinary quantum mechanics (except in the most crazy versions of it), there is something outside of our minds—the measuring devices—and they are in states that are perfectly definite 'after measurements'. It is just that there is nothing else; in particular nothing physical, that these measuring devices are made of. Or rather, there may be something 'out there' but, like the *Ding an sich*, it is radically unknowable.

Note that, as the authors point out, there is no 'classical limit' of ordinary quantum mechanics; indeed, if there is nothing out there, nothing can be a limit of that nothing. Particles that do not exist cannot acquire trajectories just because some limit is taken in some equation.

Now, there is no way to refute a priori such a view. Maybe the world is unkind to us and does not let us know its secrets. Who are we, but somewhat evolved animals, and if cats and dogs cannot understand, say, classical mechanics, why should one expect humans to be able to understand the quantum world? But there are several oddities here. First, there is a purely psychological one. When one reads the pronouncements of the Copenhagen school and their followers, one cannot but wonder at the enthusiasm with which some physicists celebrate what is in fact the ultimate defeat of physics and the end of science: the world out there being radically unknowable. Another oddity is that, if the quantum world is unknowable, it is not because it is like some ancient period of history about which most documents are lost; quite the contrary, one finds in quantum physics some of the best tested predictions in the whole of science and nearly all of modern technology is based on our knowledge of quantum mechanics. Finally, when one listens to physicists, they speak very much as if there were something out there that one can talk about: particles are sent in this or that direction, with a given spin or polarization. Of course, all this can be translated into a language about 'possible results of measurements', but is it really true that there nothing more to the physicist's day-to-day language than this translation?

In fact, if most physicists do not seem to be bothered by this radical absence of ontology in quantum mechanics, it is probably because they think that, contrary to the official doctrine, physical systems do have quantitative properties (like energy, momentum, spin, etc.) and that properly designed experiments reveal their numerical values. In this view, let us call it the *naive* one, the meaning of the wave-function is simply that it gives the statistical distribution of the values that those properties have, *prior to measurement*. Unfortunately, for reasons that were spelled out in the 1960s by Bell and Kochen and Specker, this view is simply contradicted by experiments.

Now, to the book: apart from occasional, but sharp, criticisms of the nonsense that often accompanies standard quantum mechanics discourse, it offers a detailed, pedagogical, and comprehensive discussion of a solution to the conceptual problems of quantum mechanics: Bohmian mechanics. In a nutshell (as one of the authors, Dürr, once told me), in Bohmian mechanics, *particles move*. Indeed, in Bohmian mechanics, particles have positions and therefore trajectories (and also velocities). Their motion is guided by the wave-function, which itself evolves in the usual way, according to Schrödinger's equation. That is all that the theory says.

Does Bohmian mechanics solve the problem of quantum mechanics discussed above? Yes, and in fact, in a rather straightforward way—since particles move, they and their 'measuring devices' are always in definite states (described by their positions). So we can analyze what happens during an experiment and we find that, contrary to the naive view, an experiment, in general, does not reveal a pre-existing property of a system (and therefore should simply not be called a measurement). It is rather an interaction between the system and the 'measuring device', whose statistical results can be predicted on the basis of Bohmian mechanics and which coincide with the results of the usual quantum algorithm.

The ultimate irony is that it is precisely Bohmian mechanics that makes it possible to give an accurate meaning to the intuition of Bohr and others about the 'active' role of the 'measuring devices'. However, to understand this role, one needs to discuss what is going on during a 'measurement' and not consider the latter simply as a black box or as a *deus ex machina*.

Another nice feature of Bohmian mechanics is that it is, in a very explicit and natural way, *nonlocal*, namely it includes a real but subtle form of action-at-a-distance. This is often taken to be an argument against Bohmian mechanics, but that is because people often misunderstand the content of Bell's theorem, which says that any theory about the world has to be nonlocal (in precisely the sense that Bohm's theory is nonlocal). Incidentally, Bell was driven to his result by his desire to see if one could do better than Bohm, i.e. find a theory that describes the world in the same way that Bohm's theory does, but without this nonlocal aspect. He found out (and proved) that one cannot. Incidentally also, the only way that ordinary quantum mechanics avoids being nonlocal is by not speaking about anything but 'results of measurements'. In that language, it is not clear what an 'action' could be and therefore what an 'action-at-a-distance' could be. Otherwise, ordinary quantum mechanics is just as nonlocal as Bohm's theory. But refusing to discuss a problem by restricting oneself to a language that is so poor that the problem can no longer be formulated in it is not usually considered a legitimate way to solve that problem.

Sometimes people ask what Bohm adds to ordinary quantum mechanics, since the predictions of both 'theories' are the same. In view of the above discussion, one might as well ask what is added to classical physics by assuming that the moon is there when nobody looks at it. Obviously, if one thought that the moon behaves as it does, but goes in and out of existence depending on whether someone looks at it or not, the 'observations' in the two 'theories' would be the same. But this new 'theory' would, of course, be considered crazy. The proper way to understand the relationship between Bohmian mechanics and ordinary quantum mechanics is to view the latter as an amputated version of the former: forget about the positions of the particles, i.e. about reality, focus only on 'measurements', and create all kinds of paradoxes, conceptual problems and bad philosophy.

This book contains a lot more than the best existing exposition of Bohm's theory. It contains a very pedagogical discussion of all the needed mathematics (Hilbert spaces, operators, etc.), but also of the nature and the role of randomness in physics, in particular in statistical mechanics and in the explanation of the law of increase of entropy. It also summarizes classical physics and electromagnetism. The book is written for people having a solid background in physics and mathematics, even though it also contains a lot of good philosophical observations.