James T. Cushing, *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony.* (The University of Chicago Press, 1994).

Reviewed by Laurence I. Gould

Ever since I was an undergraduate learning quantum physics (QP), the thought was unpalatable that such a theory had to be interpreted via the Copenhagen school. This was because Copenhagen's interpretation of the quantum physical processes displayed a certain lack of causality and determinism. As a result, although I could apply the formalism of QP I could never integrate the Copenhagen (or "standard") interpretation into my world view.

My first glimpse of an alternative was David Bohm's early work, written for the layperson, "Causality and Chance in Modern Physics." Since that time there has been much written by Bohm and others regarding his ("causal;" sometimes also referred to as the "ontological") interpretation of QP. But the book by James T. Cushing is the most comprehensive that I have seen in explaining the philosophical and methodological differences between Bohm's interpretation and the standard interpretation of QP. It also goes far in explaining why Bohm's views have generally gotten such a cool reception over the more than forty years since he proposed them (in papers published in the Physical Review of 1952).

Part of the reason, as Cushing explains, is the temporal order in which the interpretations appeared (the standard interpretation came first). And another part of the reason, as he says, is that arguments against competing interpretations could be refuted. An example of the latter is Louis de Broglie's "pilot-wave" (ca., 1927) interpretation which considered Schroedinger's famous dynamical wave equation, along with its "wave function," as being able to account for the manner in which a moving particle is guided (or piloted, so to speak) between being emitted (from some source) and being observed (by interacting with some apparatus or with an observer). The source of the piloting was called the "quantum potential." It, in turn, appeared in another dynamical equation, called the Hamilton-Jacobi (H-J) equation, which resulted from the substitution of (a certain form of) the wave function into the Schroedinger wave equation. The H-J equation was familiar from classical (non-quantum) physics but now contained the additional quantum potential.

But why should one want to adopt a different interpretation if the standard one gives such excellent agreement with the experimental evidence? What if you are told, as part of the answer, that so does an alternative interpretation?! For the Bohm interpretation, in particular, that is just the case. Well, then the question arises - What are the arguments that could lead someone to prefer one interpretation above the other? *That* is just the issue that Cushing's book addresses. (And it is more than just an issue of what world view one happens to like). His concern is inquiring into causes for "the acceptance and rejection of observationally equivalent, alternative, and, indeed, *incompatible* descriptions or theories of our *actual* world" (p.xii).

His inquiry in the decision-making process shows the importance, not only of physics, but also of the history (as explained above, for example) and the philosophy of science.

He is careful to distinguish the "formalism" from the "interpretation" of a given theory. By "formalism" he means "a set of equations and a set of calculational rules for making predictions that can be compared with experiment" (p.9). (From this viewpoint the standard interpretation and the Bohm interpretation are really two *different* theories of QP).

He gives numerous examples of experiments described by the formalism of QP but from the frame of reference of the two different interpretations - the standard one and the one by Bohm. One striking case, described in Chapter 5, is when neutrons (emitted from the same source) go along two different well-separated paths in space and then come together in a smaller region of space ("receiver" for short). This produces an "interference pattern" (so called because of the way in which the neutron wave functions combine) whose signature is the characteristic way in which those particle are distributed with respect to the receiver. The standard interpretation, as Cushing indicates, cannot account for the details of what happens to the neutrons between the source and the receiver. But in the Bohm interpretation the pilot-wave theory of de Broglie (also described by Madelung around the same time) is rejuvenated and bolstered through stronger arguments. Here one can track (computationally, not by actual measurement, and *without* violating the famous Heisenberg Uncertainty Principle!) each particle at every instant between the source and the receiver. This is done by computing the quantum potential plus the particle's initial conditions and then using the H-J equation (or Newton's Second Law of Motion) to find the particle's position at each instant. (The term "causal" interpretation is, therefore, well placed. But there is an addition a later version of the theory that also has a stochastic element to it). Thus one can compute each particle's trajectory between source and receiver. The standard interpretation, on the contrary, can say nothing about the trajectory. In fact if, as is consistent with some of the Copenhagen advocates, one takes the radical empiricist position of some positivists then the concept of trajectory simply has no meaning.

Cushing points up the influence of philosophy in one's doing of physics through his analyses of specific cases. For example, in his comments on the Einstein-Podolsky-Rosen paper (p.25), Cushing displays this connection by critiquing both Einstein's interpretation and Bohr's interpretation. About the one he says: "So strong a commitment to separability [roughly, the independence of one event on another that is well spatially separated from it] by Einstein was ... *not* [his stress] necessary for doing science as we have traditionally known it." About the other he says: "Bohr's slip from epistemology (based on observability) to ontology (as a necessary discontinuity and as the impossibility of 'classical' trajectories throughout an interaction) was ... not only logically unjustified but also not demanded, either by experiment or by the formalism of quantum mechanics."

In the Bohm interpretation the quantum-potential approach gives rise to the causal and deterministic aspect (of the particle trajectories). But it also gives rise to what is called "nonlocality" - viz. the *instantaneous* affect of all other particles (including those of the laboratory apparatus) on one of the particles: e.g. one that is in motion, say, from the source to the receiver. Having cited the uncritical rejection of Bohm's work by many other physicists, Cushing reasonably supposes that physicists who learn that Bohm's theory is nonlocal will "reject it since it is *merely* as empirically adequate as Copenhagen and it came later" (p.157) even though it yields trajectories where Copenhagen does not. Of course one can argue against nonlocality by considering that such instantaneous effects might violate special relativity; but the issue is more complicated (as Cushing points out in his discussions about Bell's theorem) since there are also questions of whether the violation results in the ability to send *information* faster than light can travel (which would be untenable for most physicists).

Cushing devotes careful consideration to the very important question of the "measurement problem" in QP. Briefly, the Copenhagen interpretation has it that the wave function with all its components will first move continuously but then "collapse" all of its components save one - the one associated with the value of the observable (e.g. the "spin" of the particle) obtained through the measurement. He then explains why there is no such measurement problem in the Bohm interpretation. The reason comes from the ontological status given to the thing measured. All waves are still present but not where the particle is measured. As a result, those other components do not effectively overlap with (and thus cannot affect) the measurement result. So in the Bohm interpretation there is no "collapse."

In going through the book I was sorry to see none of the famous pictures showing the quantum potential and also the trajectories of the particles. These would have given the reader some immediate enforcement of the much-argued importance of particle paths in the Bohm interpretation. It is also somewhat misleading to say (as he does at the top of p.236) that a certain equation "is just the Hamilton-Jacobi form of Newton's second law of motion" because the H-J equation involves energy quantities such as the potential energy (or the quantum potential energy). It is really the vector spatial derivative (or "gradient") of the potential energy that is directly proportional to the force found in Newton's second law of motion (as he in fact indicates in the appendix cited). Finally, there are some typos I have found on pages 40, 49, 62, 63, and 69. However, these are minor detractions compared to the book's strong positive aspects.

The book can be read with profit by philosophers or historians of science who would like to know about the issues and see how scientific methodology is played out in an ongoing controversy concerning the foundations of QP. They can supplement the main body of the text by perusing the helpful, copious, and detailed end notes and (if their appetite for more is piqued) they can follow up on some of the equally copious references accumulated at the back. Readers with some background in QP can derive a further benefit through additional explanations which involve a working out of the physics related to the foundational issues presented; these being essentially confined to appendices at the conclusion of each chapter.

The reader unfamiliar with problems in the foundations of QP should be aware that although Bohm's theory has recently been rejuvenated it does have its competitors. Here is a fair sampling of them (along with some of their proponents, past or present): Besides the Copenhagen interpretation (N. Bohr, W. Heisenberg, R. Peierls, H. Stapp), there is what can be called the Statistical interpretation (John Taylor, L.E. Ballentine), the Consciousness interpretation (J. von Neumann, E. Wigner), and the Many Universes interpretation (H. Everett, David Deutsch). May you be sensitive to your philosophical presuppositions!

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