20. Hidden Variable Interpretations.

We have shown in Ch. 18 that the probability law cannot hold if all there is in the theory of matter is the wave function, governed by the basic linear equations of motion of quantum mechanics. The reason is that **to have probability, one of the potential versions of reality must be singled out** on each run, and there is no such singling out in the basic mathematics. One way to single out one version is to suppose that, in addition to the multi-version wave function, there is an objective reality, a reality that is consistent with only one of the quantum versions. ("Objective" here means there is only a *single version* of the reality.) It is this objective reality, and *not* the wave function, that determines our perceptions. Rather than being the perceived reality, the wave function is simply a mathematical intermediary that determines the possible states of the objective reality. This conceptual scheme is called a hidden variable interpretation, where the hidden (not currently accessible to experiment) variables are the mathematical descriptors of the state of the underlying objective reality.

At present, there is no experimental evidence or theoretical reasoning which shows there exists an underlying objective reality but there is also no proof that constructing such a scheme is impossible. We will describe the Bohm hidden variable model [1] because it is currently the only reasonable candidate for an underlying, single-version theory. Then we will point out its weaknesses and conclude that there are very significant barriers to constructing a successful hidden variable interpretation of quantum mechanics.

Interpretations.

One of the reasons for looking for interpretations of quantum mechanics is normally thought to be that, because quantum mechanics gives several versions of reality, some explanation of the fact that we perceive only one version needs to be given. But we have seen in Ch. 11 that quantum mechanics alone accounts for our perceiving only a classical, single-version reality. Thus the sole reason for needing an interpretation is as an explanation of the probability law. The criterion for a successful interpretation is that **it gives an explanation of the probability law without introducing any unsupported assumptions**.

Bohm's hidden variable model.

We consider first a 'single-particle' wave function obeying the simple non-relativistic Schrödinger equation. (See A20.1 for the mathematical details.) From that equation, Bohm derived a set of trajectories through space. He then assumed there is a single 'particle'—a point of matter—which follows just one of those trajectories. So in this sense the Bohm model is very close to being just like the classical picture of matter in which point particles follow curved trajectories through space. The only difference is that, instead of just electromagnetic fields and gravity determining the trajectory, the wave function also helps to guide the flight of the particle.

[Note: It is not exactly appropriate to call this point a 'particle.' All the particle-like properties—mass, energy, momentum, spin and charge—have been shown (Ch.

12) to be properties of the wave function/state vector. Thus the Bohm 'particle' is just a featureless mathematical point that follows a mathematically derived trajectory.]

Finally Bohm assumed there was a certain probability of the particle being on a particular trajectory. Under these assumptions, he was able to show that all the probabilistic predictions of single-particle, non-relativistic, non-spin Schrödinger equation quantum mechanics are satisfied. The same type of model also works even if there are several interacting particles. Thus, within its domain, —non-relativistic, no spin, no creation or annihilation of particles—Bohm's hidden variable model is completely 'successful.'

Properties of the Bohm model. [1]

Before pointing out its weaknesses, we will describe a few of the properties of the model. **(1).** First, the 'particle' moves very rapidly back and forth in the region where the wave function is non-zero. The path of the trajectory, the velocity of the 'particle' along the trajectory, and the probability of a particular trajectory are all derived, via the Schrödinger equation, from the wave function.

Note: Because quantum probability, $|\psi(x,t)|^2$, depends on the wave function, a Bohm-like model—that is, the use of a point whose motion depends on the wave function—is almost certainly *an inevitable feature of any hidden variable theory that reproduces the quantum probability* (if such a theory exits).

(2). Second, because the wave function inherently implies non-local effects, and because the trajectories depend on the wave function, this model can accommodate non-local effects, akin to those observed in the Bell-Aspect experiment (Ch. 16, A16.1).
(3). Finally, the model is contextual rather than non-contextual. In a non-contextual hidden variable model, there is an object which has, over an extended period of time, a particular property. For example, the object might be assumed to have a definite value for the z-component of angular momentum (A12.3) for some extended time in a non-contextual model. But in a contextual model—if two zero-spin particles are bound in a spin 1 molecule for example—the measured value of the z-component of spin might change with the time and place where spin is measured.

There have been a number of attempts to prove that hidden variable interpretations cannot hold. But most of them, including the work of Bell and Aspect, exclude contextual models in which the hidden variables depend in detail on the wave function. None of them invalidates the Bohm model. Thus I do not believe any of these attempts satisfactorily rule out hidden variable interpretations.

Problems with the Bohm model.

0. There is no evidence for the Bohm model (or any other hidden variable model).
00. All numerical results (except probabilities) follow from basic quantum mechanics alone, so the Bohm model makes no numerical contribution to our understanding of the structure of matter; it plays no role in determining the energy levels of the hydrogen atom, for example. Further, one can add the derivation of the particle-like properties of mass, energy, momentum, spin and charge (Ch. 12) to the successful description of matter by no-hidden-variables quantum mechanics. And also perhaps antisymmetry

and symmetry, because one needs the linearity of quantum mechanics to make sense of these properties.

It is therefore not at all convincing to say that we perceive the underlying reality associated with the hidden variables when it is the wave function that gives all the correct qualitative and quantitative properties of matter (except probability).

1. Because of their creation and annihilation, and because there is no positional probability conservation law for photons, it is not clear that the Bohm model can be applied to photons.

2. The Bohm model is not relativistic, and because of the way in which time is used, it is difficult to generalize it to a relativistic formulation (and physical theories must be relativistic).

3. One must assume a specialized density of trajectories in order to obtain the probability law. If Nature initially chose a different density, there is no argument to show that it evolves into the specialized density. (Also, it is difficult for me to visualize how—when $\psi(x,t)$ varies so much from one time to another, and when the trajectories depend very sensitively on the details of $\psi(x,t)$—how the set of trajectories could evolve to a specific density.)

The density assumed in the Bohm model is identical to the *quantum mechanical probability* density, $|\psi(x,t)|^2$. So it borders on circular reasoning to say that the probability law is derived in the Bohm model when the probability density was used in the derivation.

4. It is an arbitrary feature of the model that a 'particle' is put on just one of the trajectories. There is nothing *in the mathematics* that prevents there being two 'particles,' on two different trajectories, associated with a 'single particle' wave function.

5. Finally, there is the problem of 'conscious' perception. The wave function does not collapse and so there is a valid quantum state of the observer's brain corresponding to each outcome. There is nothing in the mathematics of the theory which says that only the version of the brain associated with the 'particle' is 'consciously aware'.

To put it conversely, an acceptable no-collapse hidden variable theory must give a convincing reason for **why** the non-particled quantum versions of the observer cannot correspond to our awareness. Such a reason is not given in the Bohm model, and I don't believe it can be given in any hidden variable model. Thus it appears to be very difficult, perhaps impossible, to explain in any non-collapse hidden variable model why the quantum versions of the brain *not* associated with the hidden variables cannot be 'consciously aware.'

Suppose we have a robot, instead of a person, that reads the detectors. In what way—aside from just declaring it so—are the 'perceptions' of the non-particled versions of the robot less valid than those of the particled version?

One might argue that perceivable reality consists solely of the underlying objective reality associated with the hidden variables; the wave functions don't correspond to perceivable reality. But to have a valid interpretation, one must explain *why* this is so, especially in light of **00** above. Why must our perceptions correspond to the particled version?

Points **3**, **4**, and **5** show there are major unsupported assumptions in the Bohm model and the situations where it can be applied are somewhat limited. So it is not, in my opinion, an acceptable interpretation.

Evaluation.

There are no physicists, as far as I know, who would say there is a satisfactory hidden variable interpretation. And there are relatively few who think this is the interpretation most likely to work. But at the same time, there are many physicists who think there are particles, separate from the wave function (with the parameters describing the particle states implicitly being hidden variables). We have seen, however, that the simple particle interpretation doesn't work.

References

[1] David Bohm, "A suggested interpretation of quantum theory in terms of "hidden variables," *Phys. Rev*. **85** 166,180 (1952).