Puzzles of quantum mechanics

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[Disclaimer: the point of the following is to bring out some of the metaphysical puzzles which result from various interpretations of quantum mechanics. Doing this involves vast oversimplification of the material. If you are interested in really understanding quantum mechanics, you should talk to someone who knows more about it than me, like a physicist. Or you can read a good book about it; I'd recommend David Albert's *Quantum Mechanics and Experience.*]

1 Classical mechanics and quantum mechanics

In understanding some of the puzzles raised by quantum mechanics, it will be important to distinguish between two different interpretations, or versions, of quantum mechanics. To understand this difference, the key notion to understand is that of the *wave function.*

Consider a simple physical system consisting of a single particle. Then a description of that system in classical physics would consist of a specification of the location of that particle. The physical theory will describe the way that system will change over time, given the relevant physical properties of the particle.

Now consider all the possible locations of the particle. A quantum mechanical description of the system will not simply assign a location to the particle, but will instead assign values to each of the possible locations of the particle. This assignment of values to possible configurations is the wave function, or quantum state, of that system. In the case of our simple system with one particle, the value assigned by the wave function to a configuration that represents the particle as in a given location x corresponds to the probability that, if we do an experiment, we will find the particle located in x. Quantum mechanics also describes the way in which a given wave function will change over time.

The principal evidence for quantum mechanics is its predictive power. If the wave function assigns a given probability n to given configuration of particles, then, if we do enough experiments, we will find that configuration very close to $n\%$ of the time.

2 The paradox of Schrödinger's cat

The principal interpretive problem of quantum mechanics is to understand the physical reality described by the wave function. An attractively simple idea is that the wave function is the complete description of the system: that there is no fact of the matter about where, precisely, the particle is, but rather that it simply lacks a determinate location. One way to think about this is to think of the particle as located 'to some extent' in each of the locations specified by the wave function.

One way to see that this cannot be right is via Schrödinger's example of the cat:

> "One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, *so* small, that *perhaps* in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives *if* meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts." (Schrödinger, 'The present situation in quantum mechanics', §5)

The idea here is this: if we are committed to the idea that at a certain time there can be no fact of the matter about whether a given quantum event — like the decay of a radioactive substance — has occurred, then we must also think that there can be no fact of the matter about whether certain observable events, like the death of a cat, have occurred, given that we can set up a system in a such a way that if the former event occurs, then the latter event must as well. But no matter when we open up the steel chamber, we never find that the cat has neither died nor failed to die; we always find that either the cat has ingested the cyanide, or it hasn't. Since there is nothing corresponding to this either/or in the wave function, it looks like it cannot be the whole story.

3 Collapse theories

One response to this sort of problem is to suggest that, at certain times, the wave function dramatically changes, and does not evolve as the relevant equations predict. The change is from a state which (to continue the above example) assigns values to several different locations to a particle, to one in which the particle is in a single determinate location. This is called a 'collapse of the wave function.'

3.1 The two-slit experiment & the role of the observer

One suggestion is that collapse occurs when the relevant system is *observed.* This might be suggested by the following version of the *double-slit experiment.* (This is a version of the experiment originally used to defend the wave theory of light against corpuscular theories.) In this experiment, we shoot photons one by one at a screen with two slits in it. Quantum mechanics (given the details of the set-up) delivers a wave function which gives equal values to the photon going through the top slit as through the bottom slit. The natural thought here is that, be that as it may, each photon must go through one or the other, but not both. The surprising result is that the photons exhibit an interference pattern despite being shot one by one, which seems to show that individual photons in some sense pass through both slits, and interfere with themselves.

But suppose that we want to investigate this phenomenon further, and place a detector in one of the slits to see if the photon is really going through that one, or not. In that case, we stop seeing the interference pattern on the screen, so it looks like the photons have stopped going through two slits at once. A natural thought is that observation of the photon has somehow changed its behavior: observation causes collapse of the wave function.

[Not all collapse theories are of the variety that explain collapse via the observer. The orthodox view among physicists is that some version of the collapse interpretation of quantum mechanics is correct, though the issue is still very much disputed.]

3.2 Schrödinger's cat, again

How do collapse theories which give a role to the observer deal with Schrödinger's cat? One thought is that once we open the box to observe the cat, we cause a collapse of the wave function, which makes it the case that the radioactive substance either has or has not decayed, which ensures that the cat has either been killed, or is cyanide-free. Thus this version of the collapse interpretation would account for the observed facts.

However, you might still think that a kind of paradox remains. For you might think that *before* we open the box and observe its contents, there must already be a fact of the matter about whether the cat is alive or dead. (Maybe the cat counts as an observer here — but then just imagine some other observable event which can be hooked up to a similar quantum event.) This seems to be a problem for the collapse interpretation.

It should be noted here, that the problem is different than for the unmodified 'wave function only' view. On that view, we get a conflict with observation. Here we get no conflict with observation, but only conflict with what we take the unobserved facts to be.

3.3 The EPR paradox

In their 1935 paper 'Can quantum-mechanical description of physical reality be considered complete?', Einstein, Podolsky, and Rosen raised the following sort of problem for the kinds of collapse theories discussed above.

In quantum mechanics, it's possible for two particles to have properties which are connected in a certain interesting way (called 'quantum entanglement'). Consider two electrons A and B, and the property of having spin up or spin down. In some situations, the wave function will deliver the following result: each of A and B have a 0.5 probability of having spin up and the same chance of having spin down. However, there is a probability of 1 that one of them will have spin up and the other spin down. Now suppose that A and B are far apart, and that we measure electron A and find that it has spin up. On the kind of theory we are discussing, the observation of A has caused a collapse of the wave function, and that's why the particle is spin up. So far, so good. But now consider the following two plausible assumptions from the EPR paper:

- If without disturbing the system we can be certain that an object has a certain property, then the object really has that property.

- If two systems are sufficiently far apart, measuring one (at a time) does not affect the other (at that time).

By the second assumption, measuring A does not affect the system of which B is a part, and in particular does not collapse the wave function in that system. However, given that we are certain that one of A and B has spin up and the other has spin down, we can now be certain, after measuring A, that B must have spin down. So, by the first assumption, we know that B really is spin down. But then it looks like the wave function does not give a complete description of physical reality — which is the result that Einstein wanted.

Could the collapse theorist respond by saying that observation of one event can cause collapse of the wave function not only there, but also in arbitrarily distant locations at the same time?

4 Hidden variables & nonlocality

Suppose, however, that you are convinced by the EPR argument, and think that the quantum-mechanical description of physical reality is not complete — i.e., that the wave function leaves something out. This is the basic form of 'hidden variables' (as opposed to collapse) interpretations of quantum mechanics. On some versions of this sort of view, particles always have determinate locations, and change in their location over time is partially determined by the wave function. On this sort of view, there is no need for collapses of the wave function; it is acknowledged at the start that the wave function gives only an incomplete description of reality, so when something is observed which is not entailed by the wave function, there is no immediate need to postulate a special event to explain this.

How would a hidden variables theorist respond to Schrödinger's paradox?

How would a hidden variables theorist respond to the EPR paradox?

Bell's theorem and nonlocality. Two puzzling aspects of nonlocality:

1. Holism.
2. The problem of nonlocality and special relativity.