Superposition & the paradoxes of quantum mechanics

PHIL 20229
Jeff Speaks

February 5, 2008

1 Some examples of quantum weirdness

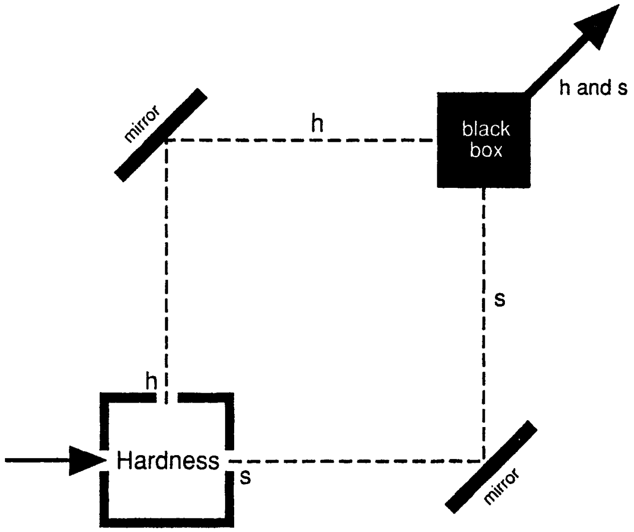
1.1 Color and hardness

In the chapter of *Quantum Mechanics and Experience* which we read, Albert describes two properties, color and hardness, of electrons. There are three important aspects of these two example properties to keep in mind:

- They are both 'on/off' properties, in the sense that every electron has some color and some hardness, and that here are only two colors, and two hardnesses, that any electron has. It is also important that t
- The two properties are *independent*, in the sense that there is no correlation between the color of an electron and its hardness.
- These properties are also *measurable*, in the sense that we can test the color of an electron repeatedly, and get the same result each time.

The surprising results begin when we see what happens when we try to measure the color *and* hardness of a single electron. Suppose we measure the color of a bunch of electrons, and then isolate the ones which are white, and then measure their hardness. As expected, since the properties are independent, 1/2 will be hard and 1/2 soft. But now if we go on to measure again the color of the electrons — all of which have previously been determined to be white — we find that the electrons are now 50% white and 50% black. It appears that something about measuring the hardness of electrons changes their color; what is surprising is that this result is constant — including the percentage — even if we use very different ways of measuring hardness.

The yet more surprising result – which Albert discusses on pp. 8-11 — comes when we consider experiments like the one that he represents via the following figure:



In this box, the entry point at bottom left measures the hardness of entering electrons, and sends the hard ones along the left path, and the soft ones along the right path. At top right the paths converge, and all the electrons exit along line 'h and s', no matter which path they took through the interior of the box. Given the previous information, consider what results of the following experiments should be:

- A stream of hard electrons are entered into the box.
- A stream of soft electrons are entered into the box.
- A stream of white electrons are entered into the box.
- A stream of white electrons are entered into the box, with the 's' route for soft electrons blocked so that only the electrons which take the 'h' route exit the box at top right.

What is the difference between the box illustrated above and a simple hardness measuring device? Does the box illustrated become a hardness measuring device when the 's' route is blocked?

Consider the third experiment above, and ask: which route did the electrons which entered the box take? A puzzle is that it seems that there is no good answer to this question. Suppose first that they all took the 'h' route. Then shutting off the 's' route would have no effect, but it does. Suppose that they all took the 's' route. Then shutting off the 's' route would lead to no electrons exiting the box, which is not what we find. This seems to leave the following three options:

1. 1/2 of the electrons took the 'h' route, and 1/2 took the 's' route.
2. The electrons all took both routes; perhaps, for example, they split in half, with one half taking the 's' route and the other taking the 'h' route.
3. The electrons all took neither route, but took some third route to the exit of the box.

What about these options fails to fit the results of the experiment?

1.2 The two-slit experiment

Another well-known experiment which shows much the same thing as the example of the box above. For a famous description of the two-slit experiment, see the excerpt from the Feynman lectures on physics on the course web site.

2 Is superposition paradoxical?

So far, we have some (very) surprising results, but not an explicit paradox. Here is an attempt to formulate one, using again the example of the experiment using the box discussed by Albert:

1. If a series of white electrons is sent through the box, all of them will still be white when they emerge along route 'h and s'.
2. If a series of electrons moves from the entrance of the box to line 'h and s', one of the following must be true: (i) they all go along route 'h' or (ii) they all go along route 's' or (iii) some go along route 'h' and the rest along route 's' or (iv) some go by way of another route.
3. If we block both routes, no electrons arrive at the destination.
4. Option (iv) is false. (3)
5. If we block the 's' route, the electrons which emerge are 1/2 white and 1/2 black.
6. If a series of electrons go through the box through the 'h' route, they will emerge 1/2 white and 1/2 black. (4,5)
7. Option (i) is false. (1,6)
8. If we block the 'h' route, the electrons which emerge are 1/2 white and 1/2 black.
9. If a series of electrons go through the box through the 's' route, they will emerge 1/2 white and 1/2 black. (4,8)
10. Option (ii) is false. (1,9)
11. If a series of electrons are passed through the box, some of which go along the 's' route and some of which go along the 'h' route, the electrons which emerge will be 1/2 white and 1/2 black. (6,9)
12. Option (iii) is false. (1,11)

C. No electrons move from the entrance of the box to line 'h and s'. (2,4,7,10,12)

The conclusion is about as clearly false as the conclusion can be.

(1), (3), (5), and (8) are experimentally verified.

(2) is the only other independent premise. So either it is false, or there is some flaw in the reasoning along the way.

2.1 Indeterminacy and collapse

So suppose we deny premise (2): maybe it is possible for the electrons to get from the entrance to the box to its exit without out following 'h', 's', or some other route. Admittedly, this is a bit weird; but maybe the truth is that, in some sense or other, the electrons simply fail to have a determinate location as they move through the box.

One immediate problem with this proposal is that, if we look in the box during an electron's progress, we always find that the electron is in some determinate location. We never find that the electron has vanished, or is somehow spread out in space.

A way to bring out this problem is 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)

One point of this example is that we can't just comfortably isolate quantum behavior in the realm of the very small, since we could, with sufficient ingenuity, rig up connections between events in this realm and observable events, like the death of a cat. But it seems that there is something impossible in the idea of a cat which neither alive nor dead, not somehow in between.

A way to respond to this problem is by saying that although the locations of the electrons might be indeterminate, they 'collapse' to a determinate location when certain things, among which are observations, happen.

Is this sort of view committed to giving observers an implausible role in determining facts about the observable world?

Does a problem still remain with the example of Schrödinger's cat? Does it make sense to say that the cat was neither alive nor dead until someone opened the box to check on it?

2.2 Another response to superposition

Can we respond to the above (very small piece of) experimental data without giving up the idea that particles have determine locations at all times? If we look at the argument above, we see that this commits us to accepting (2), which indicates that our only real option is to reject some piece of reasoning employed along the way.

One possibility here is to reject the pair of inferences from (4,5) to (6), and (4,8) to (9). In this case, we'd be rejecting the move from the premise that we get a certain observational effect by (say) blocking the 's' route to the conclusion that we would have gotten that same effect from particles which never followed that path even if it had not been blocked. If you think about it, this is a hard inference to reject. Does it make sense to reject it?

3 Nonlocality

This is connected to another odd consequence of quantum mechanics, which is more a surprising consequence than a genuine paradox. 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, and that's why the particle is spin up. So far, so good. But now consider the following two plausible assumptions (from the 1935 paper 'Can quantum-mechanical description of physical reality be considered complete?', by Einstein, Podolsky, and Rosen):

- 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 cause a collapse 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.

Does this show us that the second assumption is false?