Quantum reality is either weirdly different or it collapses

Enlarge / Eugene Wigner.
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Quantum mechanics, when examined closely, poses some deep questions about reality. These questions often take the form of thought experiments, which are later (usually much later) followed up by real experiments. One of the most difficult and deepest of these is a thought experiment proposed by Eugene Wigner in the 1960s, called “Wigner’s friend” (you don’t want to be Wigner’s friend). Now, much later, Wigner and his friend have been formalized and extended. The result sets us up with a contradiction: either reality is a lot stranger and less real at the level of quantum mechanics, or quantum states cannot possibly exist at large scales.

Don’t be Wigner’s friend

To understand why Wigner shouldn’t have any friends, we have to first dive into some details of quantum mechanics. Imagine measuring the spin of a single electron. Spin has an orientation in space, but it is not possible to measure that orientation. Instead, we have to *choose* an orientation and

measure the spin along that orientation. So we might ask an electron if its spin is vertically upward or downward. The result (all else being equal) will be either up or down with 50 percent probability.

Let’s say we measure the spin and find that it is up. Any subsequent measurements will confirm it is up, as well. The measurement has *defined* the vertical spin component (a process often called wave function collapse). But it says nothing about the horizontal component of the spin—the horizontal component will remain in a superposition of left and right spins. That means that if we rotate our apparatus so that we are measuring spin left and right, the result will be random—the electron will be either spin-left or spin-right with 50 percent probability.

This is a relatively simple experiment to do, so Wigner grabs his friend, Alice, and places her in a sealed laboratory. Alice measures the spin of a stream of electrons that are prepared in a superposition state. Wigner is outside the laboratory and will measure the entire laboratory. Alice, before passing out, determines that an electron is spin-up. But Wigner hasn’t made a measurement, so he sees Alice in a superposition of having *measured* spin-up or spin-down. When Wigner makes his measurement, hypothetically, he could end up with a result where Alice measured spin-down when in fact she measured spin-up.

Two “facts” contradict each other, but both are based on reality. Wigner’s solution to this problem was that the quantum state cannot exist at the level of the observer: the superposition state must collapse before that occurs.

Extending Wigner

The newly published extended version combines the original Wigner’s friend thought experiment with John Bell’s thought experiment (Bell’s thought experiment is old enough that it is

now routinely tested in experimental physics). Bell's experiment is a bit more complicated than Wigner's friend experiment, combining the idea of superposition and entanglement. Let's imagine that I have two electrons that are entangled. That means they have a combined quantum state, one that is only defined by the two electrons together. As an example, the entanglement process might result in two electrons with a total spin of zero.

That means they are in a superposition of up-down and down-up. If I measure one of those electrons to spin up, then the other automatically is spin-down. When performed correctly, the Bell experiment shows that it is impossible for the spin of the electrons to be pre-determined. They have to be in a superposition; when measured, they have to randomly choose an orientation.

Bell experiments have been performed with vast separations between where the particles (usually photons) are measured, making it impossible for information to travel between the two ends of the experiments without moving faster than light. Indeed, the last twenty years have seen a systematic closing of possible gaps in Bell experiments.

In the extended Wigner's friend experiment, the two friends perform Bell's experiment on an entangled pair of particles in separate sealed laboratories. Two Wigners (otherwise known as super-observers) then measure the laboratories and compare results. The measurement results reveal the correlations between the entangled pair, filtered by the wave function collapse of the two observers.

So what is this reality thing anyway?

What Wigner and Bell tell us about reality requires some thought. Physicists generally describe reality by a set of

mathematically defined conditions. For instance, causality tells us that an effect should be preceded in time by a cause. Locality says that causes propagate at the speed of light: if a photon cannot travel between the location of the cause to the location of the effect before the effect occurs, then it violates locality (and, potentially, causality).

Now we must also consider things like measurements. The researchers define the absoluteness of observed events, meaning that what I observe is real and does not depend on anything else. They assume that there is no super-determinism (we make free choices) and locality is still operative. The researchers refer to this trifecta as local friendliness.

The researchers used mathematical definitions of these statements to calculate the limits on local friendliness. They show that under the right conditions, correlations that violate these limits will be observed in the extended Wigner's friend experiment. Their laboratory experiments confirmed that these violations do in fact occur. Local friendliness is not how the Universe operates.

If we reject local friendliness, then we have to make some decisions. We have to accept some of the following possibilities: an observer's measurements are not necessarily real, reality is not local, super-determinism is real, or quantum mechanics ceases to function somewhere before macroscopic observers get involved.

Huh?

To extend on that last paragraph: the researchers' version of Wigner's friend was not actually a macroscopic observer—it was a photon, which is an inherently quantum object. It's possible that the full thought experiment with macroscopic observers in a quantum state is simply prohibited by some unknown law of physics. On the other hand, it's not beyond the realm of possibility (according to the researchers) that an artificial

intelligence on a quantum computer could be considered a macroscopic observer that is still in a quantum state, meaning we could extend testing of this in the future.

However, the bigger point is that reality may depend on quantum effects washing out before they become too large. The alternatives are that we have much less free choice than we think we do, which is a bit unpalatable. Beyond that, we have to reject locality and maybe causality, which might be even more painful for physicists.

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