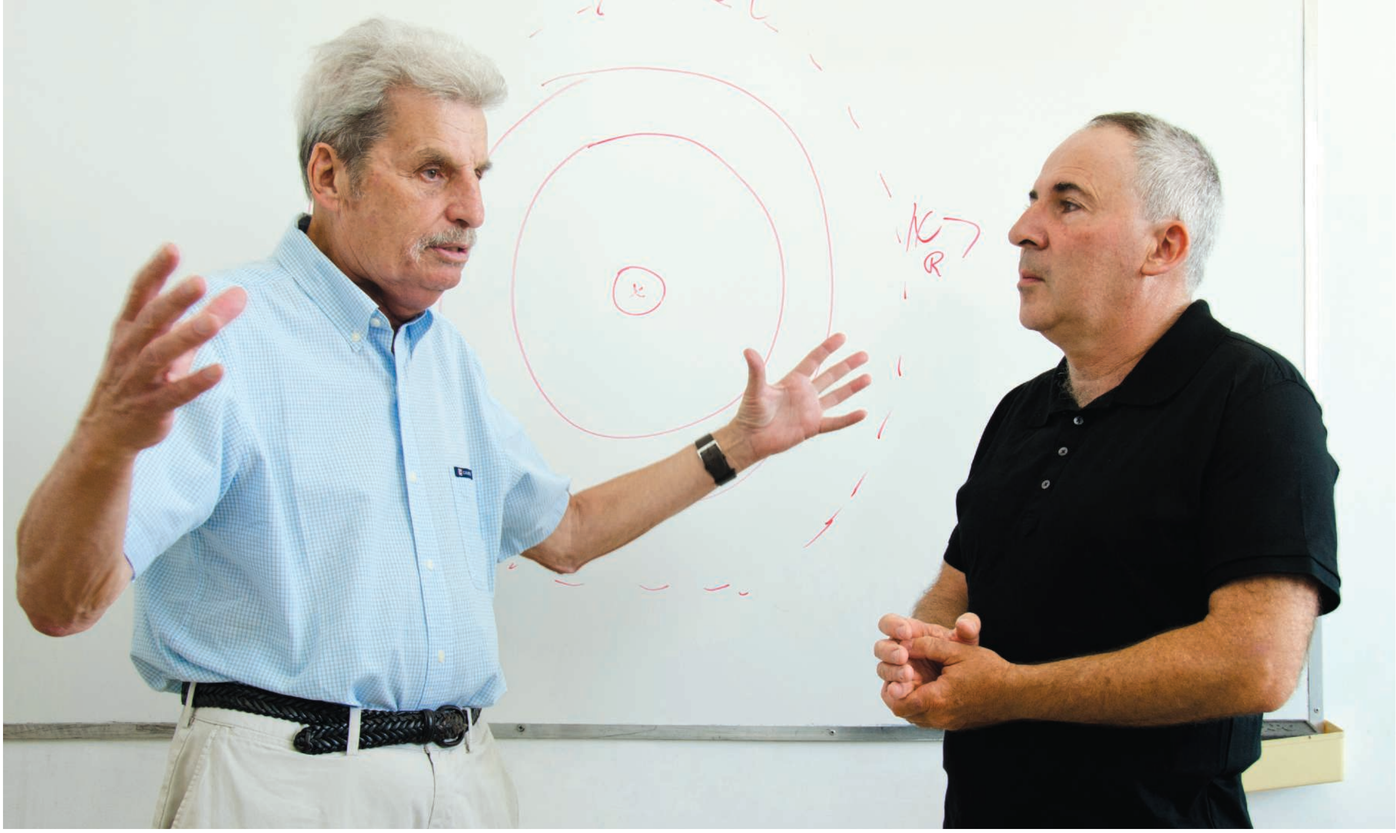

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PHYSICS

Furtive Approach Rolls Back the Limits of Quantum Uncertainty

You cannot measure a quantum particle without disturbing it. Or can you? Weird "weak measurements" are opening new vistas in quantum physics

If you know only one bit of quantum mechanics, it's likely this: You cannot make measurements on a tiny thing like an electron or photon without disturbing it. That rule of thumb puts the famous uncertainty principle into practice. For example, you can't know both exactly where an electron is and how fast it's moving, because measuring its position gives the particle a random kick that renders its momentum unknown. But does the rule always hold? Perhaps not.

Twenty-three years ago, three theorists invented a scheme that, they predicted, would enable experimenters to make "weak measurements" that do not disturb a quantum object. That idea flies in the face of the standard quantum theory, and for decades it remained a controversial sidelight little noticed by most physicists. But lately, experimenters have used weak measurements to produce a variety of surprising results. "The whole idea was so strange that people tried to pretend it didn't exist," says Sandu Popescu, a theorist at the University of Bristol in the United Kingdom. "But in the past couple of years it's become appreciated."

Weak measurements are surprisingly powerful. Researchers have used them to make measurements with mind-boggling precision, to resolve apparent paradoxes posed by quantum mechanics, and even to probe things previously thought impossible to probe directly, such as the quantum wave, or "wave function," that describes a particle. Nothing in the protocol of weak measurement breaks the rules of quantum mechanics. However, the scheme provides a way to wring more information from the theory and to sidestep some of the prohibitions drilled into the heads of physics students. "We're all trying to look behind the complex mathematical structure of quantum mechanics to understand more fully what we can measure," says Aephraim Steinberg, an experimenter at the University of Toronto in Canada. "It may sound crazy if you've learned too much quantum mechanics."

However, weak measurements themselves can be as mind-bending as other aspects of quantum mechanics. For example, they provide self-consistent explanations of paradoxical experiments, but those explanations rely on negative probabilities, a concept that many physicists find unpalatable. "People aren't sure how to interpret the weak measurement," says Jeff Lundeen, a physicist at the Canadian National Research Council in Ottawa. "What does it mean?"

How to make a weak measurement

Even before weak measurement came along, the quantum realm was plenty weird. For example, your car can sit in only one parking lot at a time, but an atom or other quantum particle can be in two places at once or spin in opposite directions simultaneously. You can't observe that bizarre behavior directly, however. Like a hammer, a standard measurement squashes a delicate two-ways-at-once state and leaves the tiny object in either one state or the other.

Suppose you want to measure the spin of silver atoms. Quantum theory tells you that each silver atom has exactly half of a fundamental amount, or quantum, of spin. And the atom's axis of rotation can point in any direction, like a gyroscope's. To measure that direction, you need to link the spin to something else that will act as a "pointer," like the one on a dial. For example, you can "couple" an atom's spin to its motion by running the atom through a magnetic field whose strength varies from place to place. The field will tug the atom in one direction or another depending on which way it is spinning. So if you shoot a beam of atoms that are all spinning the same way through such a magnetic field, the beam's deflection should serve as the pointer to reveal the spin.

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Originators. Theorists Yakir Aharonov (*left*) and Lev Vaidman invented weak measurements.

But if you do the experiment, that's not what happens. Instead, the magnetic field splits the beam in two (see figure, below). What's going on here?

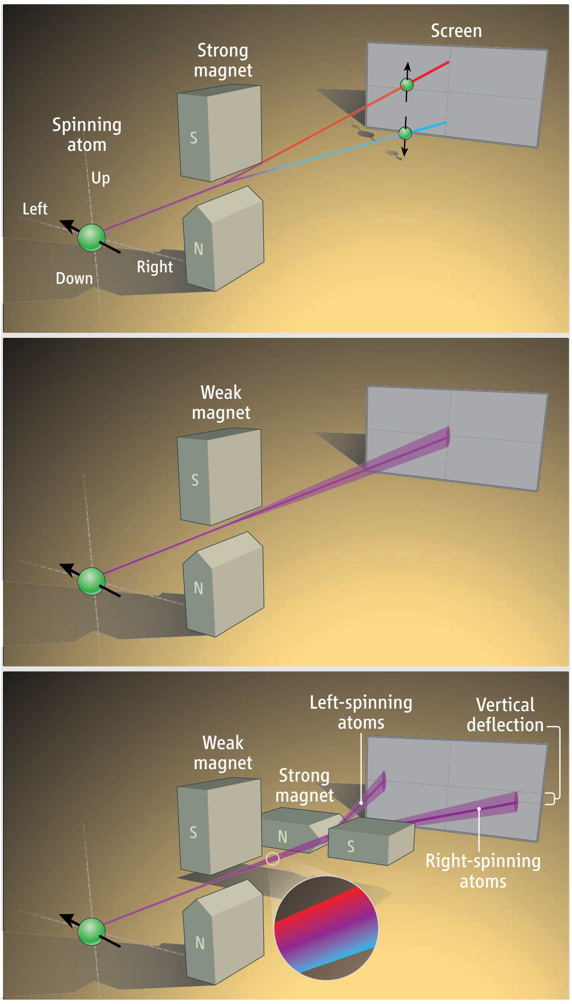
You've run headlong into quantum weirdness. Quantum theory states that each atom can spin in opposite directions at once—its axis pointing, say, up and down. Not only that, but when the atom is spinning in any arbitrary direction, its "quantum state" can be described as a specific mathematical combination of any two opposite directions. For instance, spinning on an axis pointing to the right equals the 50-50 combination "up plus down," and spinning to the left equals "up minus down." A strong vertical magnet randomly "collapses" that both-ways quantum state, leaving each atom spinning either up or down and deflecting it accordingly. The intensities of the two beams then reveal the amounts of up and down in the atoms' quantum state.

Such a "strong" measurement obliterates the original up-and-down state, however. To avoid that disturbance, an experimenter would have to weaken the magnetic field until it merely spreads the beam and ever so slightly deflects it. But the less-intrusive scheme reveals little about the atoms, and for decades physicists considered it a nonmeasurement.

Then, in 1988 theorists Lev Vaidman and Yakir Aharonov, both now at Tel Aviv University in Israel, and David Albert, now at Columbia University, devised a way to milk information from such a feeble measurement. "If you do a measurement, you believe that the more information you get, the bigger the disturbance," Aharonov says. "But there is a limit in which you can find out everything about the ensemble without disturbing any of the particles in it."

The key is to follow the weak measurement with just the right strong measurement. In the case of the spinning atoms, after applying the weak magnet to spread the beam vertically as before, an experimenter should pass the beam through a strong magnet tipped sideways. The second magnet splits the atoms into two beams, one with spins pointing left and the other with spins pointing right. Suppose the atoms originally had their spins pointing very nearly to the left. Then the second magnet will send most of the atoms into the left-spinning beam, which will reveal nothing new.

A few atoms, however, will end up in the right-spinning beam, and they will tell a richer tale. That's because the weak magnet doesn't completely separate the up and down components of the atoms' original wave function. The not-quite-separate waves then interfere with one another in a way that greatly amplifies the vertical deflection of the right-spinning beam to reveal the mixture of up and down. Thus, the weak vertical magnet produces a robust measurement without flattening the atoms' quantum state (although the second magnet does collapse it).



DIY. A standard measurement (*top*), a nonmeasurement (*middle*), and a weak measurement of a beam of spinning atoms (*inset*, interfering up [red] and down [blue] quantum waves).

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It's the interference that makes the whole scheme work. And for a given initial state of the atoms, experimenters can make that interference blossom by carefully "postselecting" a final state. "Postselection is a trick to amplify the weak measurement," Vaidman says. The key is to make the final state of the atoms nearly as different as possible from the initial state—just as in the spinning-atoms experiment, the initial almost-left-spinning state and final right-spinning state are nearly opposites. Even then, the deflection remains smaller than the width of the spread-out beam, so experimenters can't measure it by running a few particles through their rig. Instead, they must measure the average deflection of many particles in the feeble right-spinning beam.

All this might seem like much ado about nothing if a weak measurement provided the same information as a traditional measurement. But a weak measurement reveals more. A strong measurement reveals only the ratio of up and down in the atoms' original state. The weak measurement reveals the mathematical relationship between the two components—for example, the "plus" or "minus" in the right or left states. It's as if an ordinary measurement traces the silhouette of the wave function or quantum state, whereas a weak measurement yields a color photo of it.

Mind-boggling precision

The basic idea applies to any quantum particles, Vaidman says. Experimenters need only preselect and postselect states that are sufficiently different and sandwich between them a measurement for which, curiously, either state would yield an uncertain result. For example, photons can be polarized so that the electric field in them corkscrews to the right or to the left as the particles zip along. So physicists can preselect photons in the "right plus left" state and postselect those in the "right minus left state." And they can expose the beam to an interaction that, say, would tug right- and left-polarized photons in opposite directions.

That's exactly what Onur Hosten, now at Stanford University in Palo Alto, California, and Paul Kwiat of the University of Illinois, Urbana-Champaign, did to observe a new bit of physics called the spin Hall effect for light. In it, light passing at an angle from air into glass shifts sideways in a direction that depends on whether the light is left- or right-polarized. Hosten and Kwiat used the amplifying effect of weak measurement to observe that atom's-width shift, as they reported in 2008 in *Science* (8 February 2008, p. 787).

The advance highlighted the potential of weak measurements to produce exquisitely precise results. That might sound paradoxical, as by design the weak measurement reveals almost nothing about the state of each individual quantum particle passing through an apparatus. What can be measured precisely, however, is not the state of the particles but the strength of the coupling to the pointer, says Andrew Jordan, a physicist at the University of Rochester in New York state. For example, in the spinning-atoms experiment, researchers can measure the gradient of the magnetic field, which couples the atoms' spin to the beam's deflection.

Exploiting that fact, Jordan and colleagues used weak measurement in an optical scheme to detect changes in the angle of a mirror as small as 400 femtoradians, as they reported in 2009 in *Physical Review Letters*. To grasp how precise that is, Jordan says, suppose you used a mirror to direct a laser beam from Earth to the moon. Then changing the angle of the mirror by 400 femtoradians would cause the laser spot on the moon's surface to move by the width of a human hair.

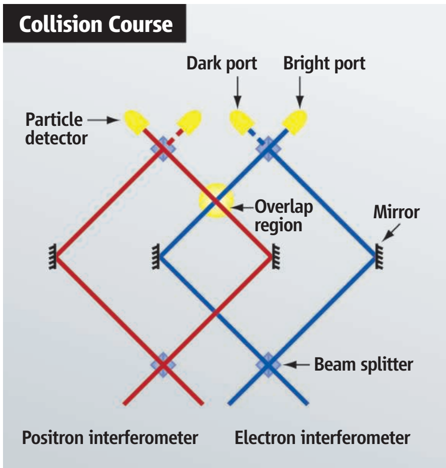
Weak measurement may soon find everyday applications. Jordan's scheme to measure the deflection of a light beam can also measure light's frequency, which determines how much a prism will deflect a beam. His team can already measure frequency as precisely as the best commercial devices. "You can use an expensive spectrum analyzer or weak measurement," Hosten says. "But one costs $30,000 and the other a few thousand."

A fresh take on quantum conundrums

Weak measurements seem to resolve some of the apparent paradoxes of quantum theory. For example, it might seem obvious that a particle has a position even before its position is measured. But quantum mechanics forbids that commonsense notion. In 1992, Lucien Hardy of Durham University in the United Kingdom dreamed up a "thought experiment" to drive that point home.

Imagine firing electrons one by one through an interferometer, a device that lets a particle in through a single entrance and then sends it down two diverging paths (see figure, above). Before the exit, the paths merge again and the quantum waves describing the electron recombine. If the paths have the right lengths, the waves will interfere so that the electron always exits through one of two "ports." Imagine further that you have an identical setup for antielectrons, or positrons, right next to the first device.

Finally, suppose one of the paths for the electrons overlaps with one for the positrons so that the particles can collide. The particles' interaction would muddle the interference of the wave in the electron's interferometer so that the electron would sometimes come out of the wrong, "dark" port. So would the positron. In fact, if the interferometers overlap, then quantum mechanics predicts that sometimes both particles will emerge from their dark ports.



Mind-bender. The setup for Hardy's paradoxical experiment, as described in the text.

But that's crazy. To emerge from the dark ports, the electron and positron had to interact. But in that case, as particle and antiparticle, they should have annihilated each other and disappeared. Nevertheless, quantum mechanics predicts that when both particles come out the dark ports, a standard measurement would reveal with certainty that the electron passed through its overlapping path. The same is true for the positron. So quantum mechanics seems to demand that both particles go through their overlapping arms, even though that leads to their destruction.

Standard quantum theory resolves this paradox in an iron-fisted way: It forbids "counterfactual" arguments about measurements that weren't actually made. Detecting the electron in its overlapping path collapses the quantum state describing the two particles so that the positron is not in its overlapping arm. By obliterating the original state, the measurement renders invalid any speculation about what would have happened had the experimenter also looked for the positron in its overlapping arm. If you didn't look to see if the positron was there, then you can't assume that it was—even if that's what a measurement surely would have shown. Thus, Hardy argued, quantum theory won't allow you to talk about a particle's position before it's measured.

Or will it? Weak values offer another way around this problem, as Aharonov and colleagues explained in 2002. The trick is to postselect the events in which both particles come out the dark ports and make weak measurements of which paths the particles go down. Simultaneous weak measurements will then show that the probability of finding the electron in its overlapping path and the positron in the nonoverlapping path is 100%. Likewise, the probability of finding the electron in its nonoverlapping path and the positron in its overlapping path is 100%.

Once gain, the mind strains. A total probability of 200% seems to suggest that there are *two* pairs of particles inside the apparatus when only one pair went in. Not to worry: Weak measurements also show that the probability of finding both particles in the nonoverlapping paths is –100%, reducing the total probability to 100% and the number of pairs back to one.

That analysis resolves the paradox with no ban on counterfactual reasoning and what you can talk about—if you're willing to accept negative probabilities. "Weak values have this consistency that standard quantum measurements don't," says Lundeen of Canada's National Research Council. "If you're comfortable with negative probabilities, then you're happy."

This might seem like a moot point, except that 2 years ago, Toronto's Steinberg and Lundeen performed the experiment. They used weak measurements on photons instead of electrons and positrons, mimicking the electron-positron annihilation with a phenomenon in which a crystal will absorb two photons that pass through it simultaneously, but not one photon at a time, as they reported in January 2009 in *Physical Review Letters*. Three months later, Nobuyuki Imoto of Osaka University in Japan and colleagues reported similar results in the *New Journal of Physics*. The results conform to predictions, negative probabilities and all.

A new quantum reality?

Not surprisingly, weak measurements have been controversial from the beginning, although not in the way one might expect. The very idea of a negative probability seems nonsensical, but Vaidman quickly points out that the weak measurements are not true probabilities. Rather, he says, the negative value indicates that the pointer used to make the weak measurement moves in the direction opposite to the direction experimenters would expect if a particle were present. In the end, negative probabilities aren't so hard to live with, other researchers say.

Instead, the real debate focuses on the claim that, in a sense, weak measurements pull back the veil imposed by standard quantum theory and allow physicists to begin to say something about the exploits of individual

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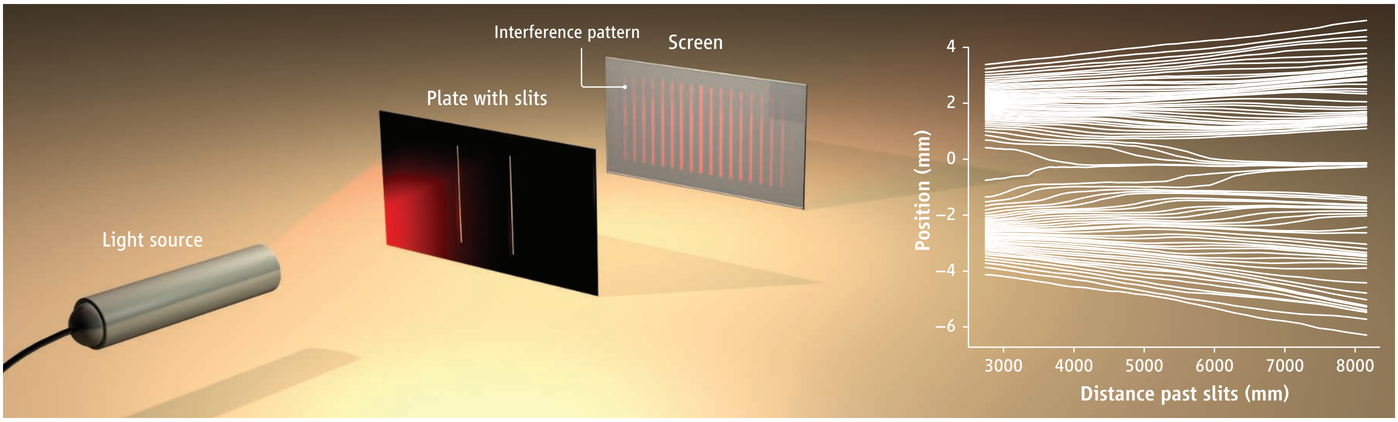
particles. Vaidman and Aharonov assert that weak measurements are "elements of reality" that reveal the true states of individual particles. So, for example, in Hardy's paradox, the weird probabilities apply to each pair of particles going through the apparatus, and, to a certain extent, physicists can begin to talk about how a quantum particle gets from one end of it to the other—something that is generally forbidden by standard quantum theory.

Not so, says Ruth Kastner, a philosopher of science at the University of Maryland, College Park. To make a weak measurement, physicists must study scads of identically prepared particles in an ensemble. So by definition, a weak measurement is a statistical average that has little to do with reality so construed. "These values do not apply to any particular particle," Kastner says. In claiming they do, Vaidman and Aharonov "pushed something a little farther than it would go," she says.



Two-slit redux. Each photon goes through both slits and has no trajectory, yet weak measurements trace the photons' average trajectories (graph, *right*).

Aharonov responds: "I think she's totally confused." As weak measurements do not disturb a system's wave function, they necessarily characterize each particle in the preselected and postselected ensemble, he says. "You can't say it's not a real property of each of these," he says. "Then there is no other way to explain what's going on."

In fact, Aharonov goes further. When developing the concept of postselection, he and Vaidman imagined the preselected state evolving forward in time and colliding with the postselected state evolving backward in time. Such backward-evolving waves are more than a trick for making calculations, Aharonov argues; the future really can affect the present. "I believe you have to think about [the backward-going wave] as a real thing," Aharonov says.

Again, Kastner objects. In an actual weak measurement, everything is calculated after postselection. "It's all in the past," Kastner says, so there's no need for quantum waves coming from the future. However, Steinberg, among others, says Aharonov's proposition deserves consideration, as it suggests there's more information available than standard quantum theory allows with forward-evolving waves alone.

Rewriting the textbooks

Even as the philosophical debate continues, experimenters are using weak measurements to perform feats recently considered impossible. For example, Steinberg and colleagues have used weak measurement to put a new spin on the "two slit" experiment: the most famous thought experiment in quantum mechanics and a classic demonstration of so-called wave-particle duality.

In the experiment, light shines through two parallel vertical slits in a thin plate and onto a distant screen (see figure, below). The waves emerging from the slits overlap on the screen to create bright stripes where the waves reinforce each other and dark stripes where they cancel each other in a bar-code-like pattern that is a hallmark of wavelike behavior.

Bizarrely, that "interference pattern" appears even if the photons pass through the slits one by one. So each particle literally must go through both slits at once and interfere *with itself*. Only if the experimenter tries to determine which slit the photon went through—perhaps by alternately closing one slit and then the other—do the stripes disappear and the photons act like particles. Among other things, the experiment shows that one cannot know both exactly where the photon is (which slit it's going through) and what its momentum is (at what angle it emerges from the slit), making it impossible to define its path.

However, Steinberg and colleagues found a way to measure the average trajectories of many photons going through the two slits. To do that, they used a weak-measurement scheme that slightly altered the polarization of the photons depending on the angle at which they emerged from the slit. The polarization, in turn, allowed the scientists to determine the average momentum of the photons hitting each point on the screen. That was enough information for the researchers to reconstruct the average trajectories as they moved the screen farther from the slits.

The experiment, reported recently in *Science* (3 June, p. 1170), doesn't violate quantum mechanics, Steinberg says; each individual photon still goes through both slits. But it eases slightly the prohibition against talking about particle trajectories. "The textbook explanation has always been, if you don't ask [experimentally] about the photon's position in the apparatus, then you shouldn't even discuss it," he says. "I think some people are starting to reconsider that."

Similarly, in June, Lundeen and colleagues reported in *Nature* that they had used weak measurement to measure directly the wave function of photons emerging from an optical fiber. That's something that generations of physicists have learned cannot be done, as standard measurements reveal only the size or "amplitude" of the wave function and not its full mathematical complexity. "People have these hand-waving ideas of what you can and can't do," Lundeen says, "and I'm kind of surprised that they haven't been taken to task earlier for some of them."

Such results must gratify Aharonov and Vaidman, the pioneers of the field. "It looks like time has shown that we were right and that [weak measurement] is completely universal," Vaidman says. The growing body of experimental work will force physicists to rethink what it means to make a measurement, as it is no longer the simple matter taught in textbooks. That may disturb some of us who learned quantum mechanics the old-fashioned way.

–ADRIAN CHO

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