PHYSICS

Measurements Are the Only Reality, Say Quantum Tests

Hamlet would run a few lines short in a quantum-mechanical theater, where "to be or not to be" is not the question at all. The usual interpretation of quantum mechanics holds that a physical quantity—such as an electron's position or a photon's polarization direction—has no reality, or "being," until an experimenter measures its value. "To measure or not to measure," that is the question.

That script didn't sit well with Einstein, who insisted that unmeasured quantities must exist in some definite state, even though we might not know what that state is. And Einstein's view "makes so much common sense," says Anton Zeilinger of the University of Innsbruck, that even now, some physicists hold out for it. They pin their hopes on the absence of a clear-cut experimental contradiction of Einstein's attempt to inject common sense into quantum mechanics. But two new experiments are coming closer than ever before to showing that quantum "reality" is every bit as bizarre as Einstein feared.

One experiment, led by Leonard Mandel at the University of Rochester in New York, has provided the most intuitively direct test yet of the "local realism" hypothesis put forth by Einstein, Boris Podolsky, and Nathan Rosen (EPR) in 1935. Einstein and his colleagues argued that physical quantities whose value can be predicted with certainty before they are measured must have an "element of reality." By creating photons with polarizations that are correlated—making one photon predictable once another is measured—the Rochester group has trapped EPR in a contradiction. They showed that if the polarizations have any reality apart from the properties that are directly measured, the observed correlations imply yet another correlation—one that is never, ever observed. "The weirdness of quantum mechanics jumps out at you" in the work, says Paul Kwiat of Los Alamos National Laboratory.

Another new experiment, led by Zeilinger, is less intuitively comprehensible but demonstrates the strongest violation of local realism ever, in mathematical terms. Neither experiment closes all loopholes, however. "A devoted advocate of the EPR world view can squirm through," says Michael Horne of Stonehill College in North Easton, Massachusetts, because the detectors capture only a small and possibly unrepresentative fraction of the photons. But several planned experiments, designed to build on the new results, could soon close the loopholes once and for all.

JAMES MONTANUS/ UNIV. OF ROCHESTER

Quantum interrogator. Rochester's David Branning at a laser table used to probe the nature of quantum reality.

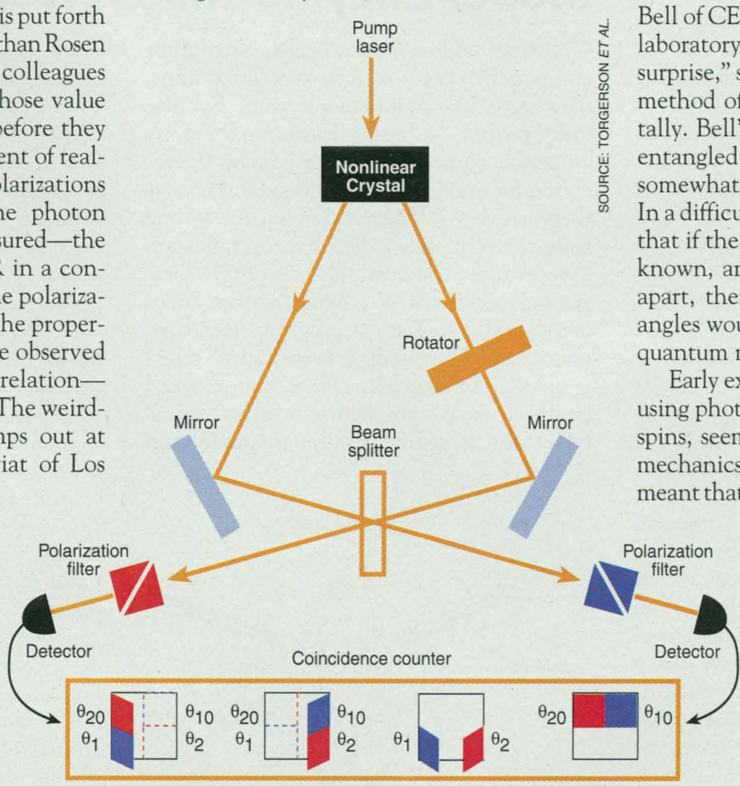
These disagreements over the nature of existence date back to the titanic debates between Einstein and physicist Niels Bohr in the 1930s. By then, the majority school of thought, led by Bohr, had concluded that unmeasured physical quantities have only a "potential" existence, with their ranges of possible values described by a haze of probability that drifts about according to the equations of quantum mechanics. Only when a measurement is made does this "wavefunction" collapse to just one value.

The EPR paper was meant to discredit this scenario by showing what strange situations it could lead to, as when two particles fly apart in such a way that their total momentum must add up to zero. In quantum mechanics, such particles are said to be "entangled." If the momentum of each individual particle has no reality before it's measured, then measuring one particle's momentum must instantly collapse the other's wavefunction down to the equal and opposite value, no matter how far apart the particles have traveled. Somehow, a distant particle instantly "knows" what value to adopt.

More reasonable than that bizarre picture, Einstein thought, was the idea that the particles had opposite, although perhaps unknown, values from the moment they flew apart. But tests of this proposal stayed in the realm of philosophical Gedanken experiments for decades, both because practical tests didn't exist and "we inherited from the '30s the feeling that ordinary physicists should keep out [of the debate] or they'll get stung," says Daniel Greenberger of the City College of New York.

Then in the mid-1960s physicist John Bell of CERN, the European particle physics laboratory in Geneva, "took everybody by surprise," says Greenberger, by formulating a method of testing local realism experimentally. Bell's test relied on two particles with entangled "spins"—a quantum concept somewhat analogous to a planet's rotation. In a difficult, abstract argument, Bell showed that if the spins had objective, although unknown, angles from the moment they flew apart, then later measurements of the two angles would show weaker correlations than quantum mechanics predicts.

Early experiments based on Bell's proposal, using photon polarizations instead of particle spins, seemed to support orthodox quantum mechanics. But inefficiencies in the apparatus meant that only a tiny fraction of the available light could be captured, and Bell's argument—although agreed to be correct—is involved enough that "the first couple times through [it] ... you wonder if somewhere the rabbit has gone into the hat," says Los Alamos's Kwiat. Since then, experimental physicists have developed better methods for producing entangled photons and more efficient detectors. And, in 1992, theorists came up with a more direct and vivid test of local re-



SOURCE: TORGERSON ET AL.

A trap for local realism. Two photons with different polarizations are mixed at a beam splitter, entangling them. Correlated photon detections (open doors) at different settings of the two polarization filters *(colors)* predict yet another correlation that is not observed (closed doors).

alism. Building on theoretical work by Greenberger, Horne, and Zeilinger, Lucien Hardy at the University of Durham in the United Kingdom constructed a test that, says Kwiat, is "brilliant in terms of being able to explain the whole thing to your grandmother."

That's the scheme that Mandel and his colleagues, Justin Torgerson and David Branning at Rochester and Carlos Monken at the Universidade Federal de Minas Gerais in Brazil, describe in the 28 August issue of *Physics Letters* A. The group sent ultraviolet laser light through a crystal of lithium iodate, a nonlinear material that can split a photon into a longer wavelength pair with identical polarizations. They then passed one photon in an occasional pair through a polarization rotator, which turned its polarization by 90 degrees, then mixed it back together with its mate at a beam splitter—a step that entangled the quantum-mechanical wavefunctions of the rotated and unrotated photons. The result was two photons composed of mixed-up pieces of the original two.

The beam splitter then sent the mixed wavefunctions down two separate arms of the apparatus. At the end of each arm lay an adjustable polarization filter and a light detector. The filter served as a measuring device by letting a photon reach the detector or blocking it, depending on its polarization.

Because each photon is a mixture of two orthogonal polarizations, it can exhibit any polarization when measured. And because the two photons are entangled, their polarization angles have a statistical correlation. When quantum theory is applied to the entangled wavefunctions, it makes specific predictions about how often the two detectors should record photons simultaneously for particular polarizer angles in the setup's two arms. If, for example, detector 1 records a photon when its polarizer is set to 74.3 degrees, then the theory predicts that detector 2 should always record a photon when its polarizer is set to −33.2 degrees. The Rochester group found that these quantum mechanical predictions hold up nicely, says Mandel.

That result doesn't create a serious problem for local-reality holdouts. For them, the real trouble comes when the experimenters look for other pairs of polarizer angles that also yield perfect coincidences. Torgerson and Branning liken the measurements to watching the opening of Dutch doors, which are split in the middle so that trays of food can be served through the top without opening the entire door. "Opening a door is like making a photodetection," says Branning. If the sections of a Dutch door represent two polarizer angles that always yield a coincidence, the top half of the door will always open along with the bottom.

Having found two pairs of polarizer angles corresponding to two doors that must swing open in this way, the researchers started checking the coincidences when one angle was chosen from each door. For certain sets of angles, they found, the bottom halves of both doors sometimes opened together. And here's the rub: The top halves never did. Yet the top and bottom of each door had swung open together in the earlier set of measurements. If the polarizations exist irrespective of measurement, detecting the bottom polarizations in both arms implies that the top polarizations should also be present, unmeasured, in the opposite arms. But in quantum mechanics, which makes no assertion at all about one set of polarizations while others are being measured, there's no contradiction at all.

"These experiments remind us not to fall into [a] comfortable, local-realistic picture," says John Rarity of the Defense Research Agency in the United Kingdom. Rarity and others point out, however, that such work rigorously eliminates local realism only under the "fair sampling" assumption, which takes the photons captured in the still-inefficient detectors to be representative of all photons present. That sends up a red flag to EPR advocates like Augusto Garuccio of the University of Bari in Italy, who collaborated for a time on the Mandel experiment. The fair-sampling assumption, if incorrect, "could be the cause of the claimed violation of the locality," says Garuccio.

That criticism is almost—but not quite—put to rest by a paper in press at *Physical Review Letters* by Kwiat along with Klaus Mattle, Harald Weinfurter, and Zeilinger at Innsbruck, and Alexander Sergienko and Yanhua Shih at the University of Maryland, Baltimore County. Using related techniques in an experiment based on Bell inequalities, these authors have observed the most extreme statistical violation of local realism ever reported. The overall detection efficiency is also the highest on record, and members of this group, along with Philippe Eberhard of the Lawrence Berkeley National Laboratory, believe this may be a step toward a loophole-free experiment within the next few years. And in independent work, Edward Fry of Texas A & M University is now building what he hopes will be a loophole-free experiment based on atomic spins rather than photons.

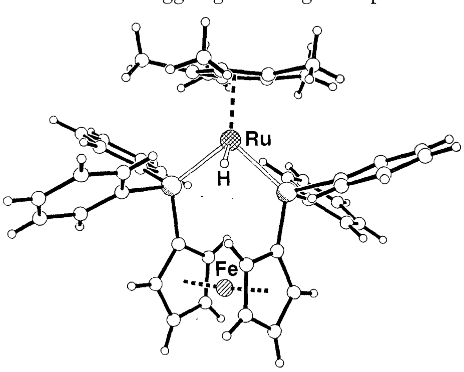
The success of these experiments may finally prove Einstein's "common sense" view to be wrong. But they won't ease discomfort with quantum mechanics. Einstein "was driven [to his conclusions] because he realized how strange quantum mechanics is," says Zeilinger. Experiments like Zeilinger's insist that the strangeness is a fact of life.

–**James Glanz**

BIOCHEMISTRY

Model Enzyme Takes Hydrogen Apart

Splitting hydrogen molecules into their components, two electrons and two protons, may seem like a simple reaction. But the exact process—a life-or-death one for many anaerobic bacteria, which depend on the reaction for energy—has remained mysterious to biochemists. They've known for a long time that enzymes called hydrogenases are involved, yet the unwieldy size of these enzymes has prevented researchers from documenting the breakup step by step with conventional spectroscopic techniques; intermediate complexes in the breakup are cloaked by the enzymes' complexity. So investigators have been struggling to design simpler and more easily observable compounds that mimic this hydrogen-splitting ability.



New metal, new model. Substituting ruthenium (Ru) for nickel made this molecule a hydrogenase mimic.

Now a group of researchers from the University of Nebraska, Lincoln, led by chemist Robert Hembre, report creating the first hydrogenase model that performs hydrogen-splitting duties. In addition to shedding light on how the enzymes work, the new molecules may be inexpensive catalysts for power systems, known as fuel cells, that convert the chemical energy in hydrogen gas directly into electricity.

The research, which will be published in the *Journal of the American Chemical Society* in January, is already drawing praise from colleagues. "It's really dynamite work," says chemist James Collman of Stanford University in Palo Alto, California. Even though the new structures are different from the natural protein, "they imitate the function of the real thing," says Collman.

The compounds, known as metal hydrides, are such good mimics because they borrow a key element from hydrogenase itself: a closely knit pair of electron-hungry atoms from a so-called transition metal. Researchers have long thought that an atom of nickel, a transition metal that's part of the hydrogenase molecule, steals electrons from hydrogen. But hydrogenases also carry an iron atom located near the nickel, which