QUANTUM PHYSICS

'Eraser' Rubs Out Information To Reveal Light's Dual Nature

Quantum mechanics has been an enormously successful theory, helping to explain everything from electronic devices to the nuclear reactions in the core of the sun. But some of its predictions nearly defy belief. Particles of light—photons—sometimes behave like waves and sometimes like particles, depending on who is looking at them and how. Stranger still, they can change their behavior in response to a decision that has not yet been made, and one photon in a pair can even appear to affect the properties of a sibling instantaneously, even if the twin is on the other side of the moon.

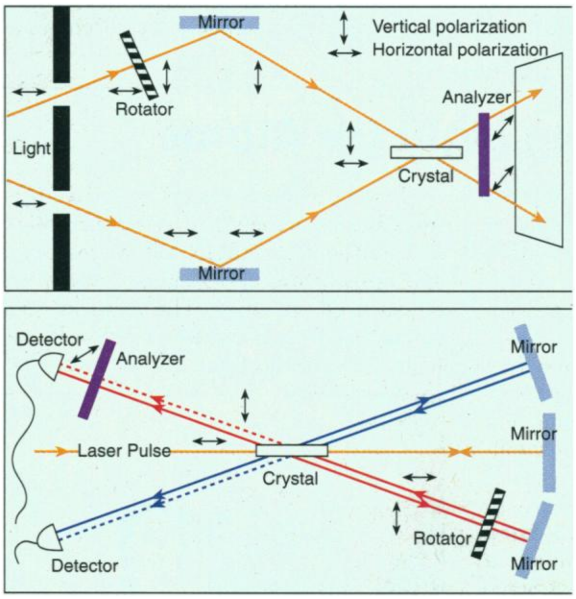
So troubling are these predictions that even though quantum theory is approaching its 100th birthday, many researchers keep probing to see if they really hold true. "It's always good to check if the world really works as amazingly as predicted by quantum mechanics," says Alain Aspect of the Institut d'Optique in Orsay, France. Adds Marlan Scully of Texas A & M University: "I only can lay claim to having understood [quantum riddles] once I do experiments and think carefully about them." But because such tests require ingenious schemes to reveal single photons or particles in the act of displaying these behaviors, experimenters have struggled to catch up with the theory.

A new experiment carried out by a team at the University of Innsbruck in Austria takes a big step toward closing the gap by dramatizing several aspects of quantum strangeness at once. The Innsbruck experiment is the latest version of what physicists have dubbed a "quantum eraser," first demonstrated at the University of California, Berkeley, in 1992 by a team led by Raymond Chiao. Like Chiao's, the Innsbruck group's eraser shows that photons' wavelike nature can be resurrected even after they have been encouraged to behave in a particlelike way.

But the researchers, led by Anton Zeilinger, piled strangeness on strangeness by devising an eraser that demonstrates "nonlocality"—the ability of an experiment in one place to influence the outcome in another regardless of time or distance—but without transmitting any signals. For Chiao this is the most intriguing feature of the new work. "The Innsbruck experiment brings out the nonlocality features, the very strangest features of quantum mechanics," he says. "It's certainly a step beyond what we did at Berkeley."

Quantum erasers are a modern version of an experiment first carried out in the early 19th century by English physicist Thomas Young. He showed that if you split a beam of light in two by shining it onto two slits, then bring the beams together again and superimpose them, a pattern of light and dark bands forms that is a hallmark of interfering waves. Young's demonstration was a blow to the view prevailing since Isaac Newton's time that light was made of particles.

But according to quantum theory, both views are right. Photons fired one by one through a pair of slits do form an interference pattern on the far side. But quantum theory



Two-way streets. Quantum eraser experiments make two light paths distinguishable with a polarization rotator, then remove this "which-path" information with an analyzer.

predicts that if the path of individual photons can be traced through one or the other of the two slits, the interference pattern will vanish. The American physicist Richard Feynman described a simple rule of thumb for this effect: If the paths are distinguishable, then the light will behave as particles, and there will be no interference. If the paths are indistinguishable, then the light will behave as a wave and interfere with itself.

The idea behind a quantum eraser—first suggested by Scully 13 years ago—is to make the paths distinguishable, but then erase that "which-path" information again before the light reaches the screen. If an interference pattern reappears, as theory predicts, it will dramatize a quantum mystery: A photon approaching the slits somehow needs to "know" whether or not there is an eraser further down the line, so it can decide whether to pass through both slits as a wave and produce interference, or traverse one slit as a particle and produce no interference. And that's just what Chiao, along with collaborators Paul Kwiat and Aephraim Steinberg, saw in 1992 when they built the first eraser setup ever.

An eraser experiment can be visualized as a two-slit experiment in which the initial beam is horizontally polarized light, with all the light waves oscillating in the horizontal plane (see upper diagram). When the split beams recombine, they produce an interference pattern. But a polarization rotator that changes the polarization of one of the split beams from horizontal to vertical will cause the interference pattern to vanish, because the two routes are now distinguishable: A photon traveling via one path is vertically polarized, but a photon traveling along the other remains horizontal.

The eraser itself is a polarization filter, or analyzer, inserted between the recombined beams and the screen. The filter cuts out some of the merged light, leaving only the component oscillating at 45° to vertical. That makes it impossible to tell whether a photon was horizontally or vertically polarized beforehand. The filter thus erases the which-path information. Interference should reappear—as it did, in the Berkeley experiment.

But Scully, for one, was not completely convinced by this arrangement because the which-path information was carried by the photons that did the interfering, making the experiment more difficult to interpret. Now Kwiat, who has moved to Los Alamos National Laboratory, along with Zeilinger and his Innsbruck colleagues Thomas Herzog and Harald Weinfurter, has unveiled a new eraser experiment closer to the spirit of Scully's idea. "The basic improvement of the new experiments is that the which-path information is not carried by what one would naively consider the 'interfering' particle. Rather it is carried by a second photon," says Kwiat. And because of the novel way the experiment exploits the creation of photon twins, it also demonstrates nonlocality.

As the group describes in the 23 October issue of *Physical Review Letters*, they fired laser photons at a light-splitting crystal that converts some of the incoming photons into pairs of identical photons with a lower energy and vertical polarization (solid red and blue lines in lower diagram). Because these photons are produced as twins, a measurement of one photon can automatically tell you about the other, with no direct measurement on the second photon. The twin beams, which exit the crystal at an angle to their original path, are reflected back toward the crystal by mirrors, but now they pass through it toward detectors.

However, not all the laser light gets converted on the first pass: Some goes straight through the crystal to another mirror and is reflected back into the crystal, giving it another crack at making photon pairs, which then follow the same path as the other beams to the detectors (dotted red and blue lines in lower diagram). The result is two different beams heading toward each detector along two different paths. Each pair of beams corresponds to a double-slit experiment. And providing there is no way to distinguish photons that might be created on the laser light's first pass through the crystal from those that might be created on the second pass, both detectors register an interference pattern.

To make one red path distinguishable from the other, the researchers put a polarization rotator in the solid red path, converting the vertically polarized light to horizontal. And sure enough, inserting the rotator makes the interference pattern in the upper detector vanish. However, the interference pattern also disappears from the bottom detector. Why? The photons are created as pairs, so when the red-path photons become labeled with which-path information, the same information becomes available for the blue-path photons. This is nonlocality at work.

To erase the which-path information, the Innsbruck team then added a 45° filter to the red path, just in front of the detector. The interference pattern then reappeared in that detector. An interference pattern did not reappear in the other detector, because analyzing the red-path photons does not erase any information from the blue path. But when the experimenters combined the readouts from both detectors, they were able to show that interference actually had been resurrected along both paths. Inserting or removing the which-path information transforms the behavior of light throughout the system, simultaneously demonstrating Scully's quantum eraser and dramatizing nonlocality.

For quantum theorists, the Innsbruck experiments offer a fine demonstration that the world really is as weird as quantum mechanics would have us believe. Leonard Mandel of the University of Rochester in New York state, who reported results of a similar experiment at a conference last June, says, "It is nice to be able to demonstrate that distinguishability is the key to determining whether you have interference." And Scully is pleased with the progress of his eraser concept: "These experiments are getting closer and closer all the time to what I had hoped we would do."

–Andrew Watson

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OPTICS

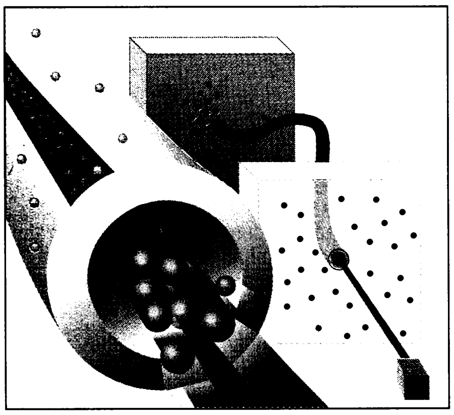
Laser Is a Guiding Light for Atoms

Laser beams have proven faithful guides for everything from smart weapons to teams of surveyors. In last week's *Physical Review Letters* (*PRL*), their path-finding abilities are on display again, but on a much smaller scale. There, a team of Colorado researchers reports using a laser to guide streams of rubidium atoms through a hollow optical fiber—a feat of control, other physicists believe, that could provide researchers in areas from quantum mechanics to nanotechnology with streams of atoms on tap wherever they are needed.

"It's a new technique that certainly has a lot of promise," says William Phillips, a physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. Such controllable streams of atoms, explains Phillips, could give nanotechnologists a new way to deliver atoms to precise positions on surfaces. They might also find uses in the new field of atom optics, where physicists split and recombine beams of atoms to explore the wave nature of matter. In the past, it took a series of magnetic or electric fields to bend the path of an atomic beam, explains Phillips. "Now you just bend the tube and make all of the atoms follow the same path," he says.

In creating their atomic guides, the Colorado researchers, led by Dana Z. Anderson and Carl Wieman at the University of Colorado and JILA, both in Boulder, and Eric Cornell at JILA and the Boulder branch of NIST, faced a sticky problem. They needed to ensure that an atom sent down a hollow fiber would faithfully follow any twists and turns without colliding with the walls, where it would stick.

To keep the atoms away from the fiber's walls, the researchers fired a laser beam along it. Laser light effortlessly follows the twists and turns of the optical fiber, because it's reflected off the walls. The light, in turn, guides the atoms. It can do so because, like all light, a laser beam creates an oscillating electric field. This oscillation causes the atoms' electrons to vibrate. If the frequency of the oscillating field of the laser light is just below the atoms' resonance frequency—a frequency at which their electrons jump from the ground state to an excited state—the atoms and the light oscillate in synchrony, and the atom is drawn to the beam. The tuning is critical: If the frequency of the laser light is above resonance, the atoms oscillate out of synch with the light and get kicked out of the beam.



ILLUSTRATOIN: K. SUTLIFF

Drawn to the light. A laser beam channels atoms along the center of a hollow optical fiber.

In their laser guiding scheme, the Colorado researchers not only tuned their laser to just the right frequency; they also tailored the beam so it was most intense down the center. As a result, atoms were attracted to the very center of the fiber, where they could slip safely past the walls. Connected to a container of rubidium gas, a 5-centimeter atomic hose of this design carried about 10,000 atoms a second, the group reported in the *PRL* paper.

To boost the precision of their atomic delivery system—and thereby make it more useful for atom interferometry and nanotechnology experiments—the researchers now hope to limit the lateral movements of the atoms even further, forcing them to travel through the hoses along just a single path. Fibers with channels even smaller than the 10-micrometer diameter of the current setup will help focus the atoms. At the same time, by taking advantage of the wave nature of matter, the researchers will make the atoms very large. "By cooling the temperature, you increase the wavelength of the atoms," says Anderson. Chilling the rubidium atoms to 100 billionths of a kelvin should fatten them up until they can just barely fit through the fiber, providing even tighter control over their path.

As a bonus, the need for a close match between the laser's own frequency and the atoms' resonance frequency means that the setup acts as a filter that accepts only one kind of atom. Others, with different resonance frequencies, are oblivious to the guiding light. By giving researchers just the type of atoms they want right where they want them, says Anderson, "this might make life a whole lot easier for doing atom experiments."

–Robert F. Service