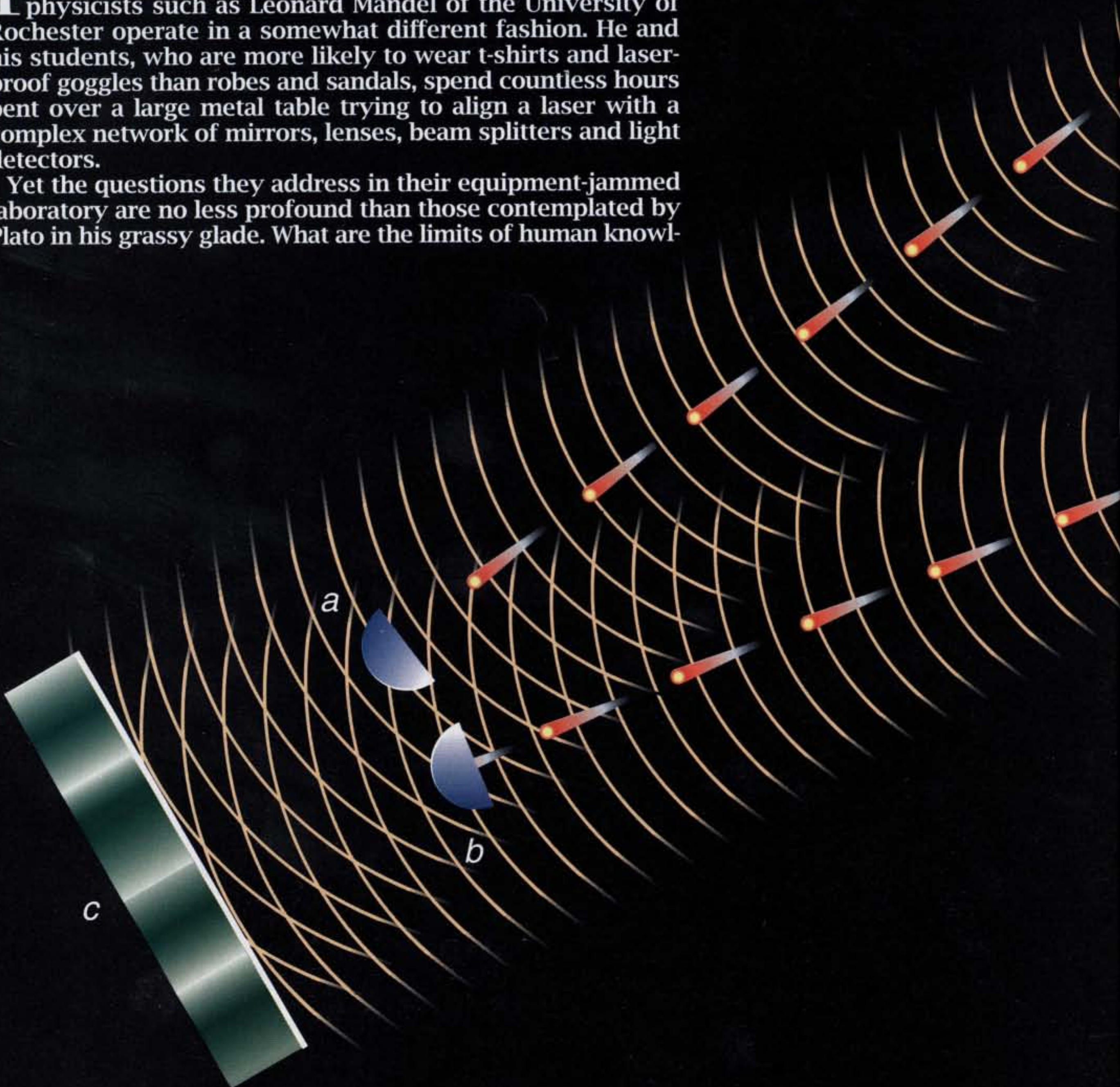
QUANTUM PHILOSOPHY

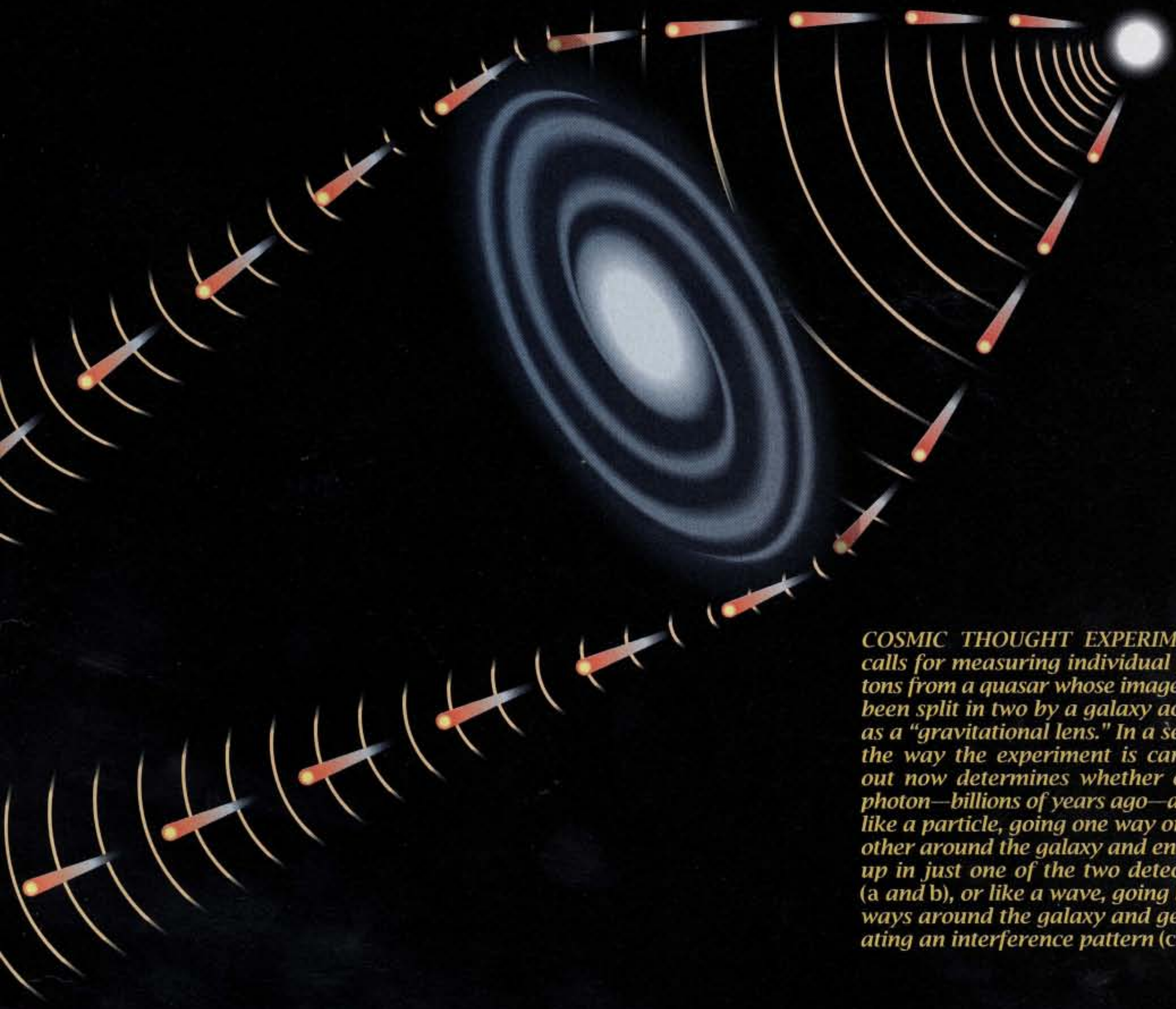
by John Horgan, *senior writer*

New experiments—real and imagined—are probing ever more deeply into the surreal quantum realm.

In ancient Greece, Plato tried to think and talk his way to the truth in extended dialogues with his disciples. Today physicists such as Leonard Mandel of the University of Rochester operate in a somewhat different fashion. He and his students, who are more likely to wear t-shirts and laser-proof goggles than robes and sandals, spend countless hours bent over a large metal table trying to align a laser with a complex network of mirrors, lenses, beam splitters and light detectors.

Yet the questions they address in their equipment-jammed laboratory are no less profound than those contemplated by Plato in his grassy glade. What are the limits of human knowl-





COSMIC THOUGHT EXPERIMENT calls for measuring individual photons from a quasar whose image has been split in two by a galaxy acting as a "gravitational lens." In a sense, the way the experiment is carried out now determines whether each photon—billions of years ago—acted like a particle, going one way or the other around the galaxy and ending up in just one of the two detectors (a *and* b), *or like a wave, going both ways around the galaxy and generating an interference pattern* (c).

edge? Is the physical world shaped in some sense by our perception of it? Is there an element of randomness in the universe, or are all events predetermined?

Mandel, being inclined toward understatement, offers a more modest description of his mission. "We are trying to understand the implications of quantum mechanics," he says. "The subject is very old, but we are still learning."

Indeed, it has been nearly a century since Max Planck proposed that electromagnetic radiation comes in tidy bundles of energy called quanta. Building on this seemingly tenuous supposition, scientists erected what is by far the most successful theory in the history of science. In addition to yielding theories for all the fundamental forces of nature except gravity, quantum mechanics has accounted for such disparate phenomena as the shining of stars and the order of the periodic table. From it have sprung technologies ranging from nuclear reactors to lasers.

Still, quantum theory has deeply disturbing implications. For one, it shattered traditional notions of causality. The elegant equation devised by Erwin Schrödinger in 1926 to describe the unfolding of quantum events offered not certainties, as Newtonian mechanics did, but only an undulating wave of possibilities. Werner Heisenberg's uncertainty principle then showed that our knowledge of nature is fundamentally limited—as soon as we grasp one part, another part slips through our fingers.

The founders of quantum physics wrestled with these issues. Albert Einstein, who in 1905 showed how Planck's electromagnetic quanta, now called photons, could explain the photoelectric effect (in which light striking metal induces an electric current), insisted later that a more detailed, wholly deterministic theory must underlie the vagaries of quantum mechanics. Arguing that "God does not play dice," he designed imaginary "thought" experiments to demonstrate the theory's "unreasonableness." Defenders of the theory such as Niels Bohr, armed with thought experiments of their own, asserted that Einstein's objections reflected an obsolete view of reality. It is not the job of scientists, Bohr chided his friend, "to prescribe to God how He should run the world."

Until recently, the prevailing attitude of most physicists has been utilitarian: if the theory can foretell the performance of a doped gallium arsenide semiconductor, why worry about its epistemological implications? In the past decade or so, however, a growing cadre of researchers has been probing the ghostly underpinnings of their craft. New technologies, some based on the very quantum phenomena that they test, have enabled investigators to carry out experiments Einstein and Bohr could only imagine. These achievements, in turn, have inspired theorists to dream up even more challenging—and sometimes bizarre—tests.

The goal of the quantum truth-seekers is not to build faster computers or communications devices—although that could be an outcome of the research. And few expect to "disprove" a theory that has been confirmed in countless experiments. Instead their goal is to lay bare the curious reality of the quantum realm. "For me, the main purpose of doing experiments is to show people how strange quantum physics is," says Anton Zeilinger of the University of Innsbruck, who is both a theorist and experimentalist. "Most physicists are very naive; most still believe in real waves or particles."

So far the experiments are confirming Einstein's worst fears. Photons, neutrons and even whole atoms act sometimes like waves, sometimes like particles, but they actually have no definite form until they are measured. Measurements, once made, can also be erased, altering the outcome of an experiment that has already occurred. A measurement of one quantum entity can instantaneously influence another far away. This odd behavior can occur not only in the microscopic realm but even in objects large enough to be seen with the naked eye.

These findings have spurred a revival of interest in "interpretations" of quantum mechanics, which attempt to place it in a sensible framework. But the current interpretations seem anything but sensible. Some conjure up multitudes of universes. Others require belief in a logic that allows two contradictory statements to be true. "Einstein said that if quantum mechanics is right, then the world is crazy," says Daniel Greenberger, a theorist at the City College of New York. "Well, Einstein was right. The world is crazy."

The root cause of this pathology is the schizophrenic personality of quantum phenomena, which act like waves one moment and particles the next. The mystery of wave-particle duality is an old one, at least in the case of light. No less an authority than Newton proposed that light consisted of "corpuscles," but a classic experiment by Thomas Young in the early 1800s convinced most scientists that light was essentially wavelike.

Young aimed a beam of light through a plate containing two narrow slits, illuminating a screen on the other side. If the light consisted of particles, just two bright lines should have appeared on the screen. Instead a series of lines formed. The lines could be explained only by assuming that the light was propagating as waves, which were split into pairs of wavelets by the two-slit apparatus. The pattern on the screen was formed by the overlapping, or interference, of the wavelet pairs. The screen was bright where crests coincided and dark where crests met troughs, canceling each other out.

But more recent two-slit experiments suggest that Newton was also right. Modern photodetectors (which exploit the photoelectric effect explained by Einstein) can show individual photons plinking against the screen behind the slits in a particular spot at a particular time—just like particles. But as the photons continue striking the screen, the interference pattern gradually emerges, a sure sign that each individual photon went through both slits, like a wave.

Moreover, if the researcher either leaves just one slit at a time open or moves the detectors close enough to the two slits to determine which path a photon took, the photons go through one slit or the other, and the interference pattern disappears. Photons, it seems, act like waves as long as they are permitted to act like waves, spread out through space with no definite position. But the moment someone asks where the photons are—by determining which slit they went through or making them hit a screen—they abruptly become particles.

Actually, wave-particle duality is even more baffling than this explanation suggests, as John A. Wheeler of Princeton University demonstrated with a thought

Revealing the Split Personality of Light

Two-slit experiments reveal that photons, the quantum entities giving rise to light and other forms of electromagnetic radiation, act both like particles and like waves. A single photon will strike the screen in a particular place, like a particle (*left*). But as more photons strike the screen, they begin to create an interference pattern (*center*). Such a pattern could occur only if each photon had actually gone through both slits, like a wave (*right*).

experiment he devised in 1980. "Bohr used to say that if you aren't confused by quantum physics, then you haven't really understood it," remarks Wheeler, who studied under Bohr in the 1930s and went on to become one of the most adventurous explorers of the quantum world.

In the two-slit experiments, the physicist's choice of apparatus forces the photon to choose between going through both slits, like a wave, or just one slit, like a particle. But what would happen, Wheeler asked, if the researcher could somehow wait until after the light had passed the two slits before deciding how to observe it?

Five years after Wheeler outlined what he called the delayed-choice experiment, it was carried out independently by groups at the University of Maryland and the University of Munich. They aimed a laser beam not at a plate with two slits but at a beam splitter, a mirror coated with just enough silver to reflect half of the photons impinging on it and let the other half pass through. After diverging at the beam splitter, the two beams were guided back together by mirrors and fed into a detector.

This initial setup provided no way for the investigators to tell whether any individual photon had gone right or left at the beam splitter. Consequently, each photon went both ways, splitting into two wavelets that ended up interfering with each other at the detector.

Then the workers installed a customized crystal called a Pockels cell in the middle of one route. When an electric current was applied to the Pockels cell, it diffracted photons to an auxiliary detector. Otherwise, photons passed through the cell unhindered. A random-signal generator made it possible to turn the cell on or off after the photon had already passed the beam splitter but before it reached the detector, as Wheeler had specified.

When the Pockels-cell detector was switched on, the photon would behave like a particle and travel one route or the other, triggering either the auxiliary detector or the primary detector, but not both at once. If the Pockels-cell detector was off, an interference pattern would appear in the detector at the end of both paths, indicating that the photon had traveled both routes.

To underscore the weirdness of this effect, Wheeler points out that astronomers could perform a delayed-choice experiment on light from quasars, extremely bright, mysterious objects found near the edges of the universe. In place of a beam splitter and mirrors, the experiment requires a gravitational lens, a galaxy or other massive object that splits the light from a quasar and refocuses it in the direction of a distant observer, creating two or more images of the quasar.

Psychic Photons

The astronomer's choice of how to observe photons from the quasar here in the present apparently determines whether each photon took both paths or just one path around the gravitational lens—billions of years ago. As they approached the galactic beam splitter, the photons must have had something like a premonition telling them how to behave in order to satisfy a choice to be made by unborn beings on a still nonexistent planet.

The fallacy giving rise to such speculations, Wheeler explains, is the assumption that a photon had some physical form before the astronomer observed it. Either it was a wave or a particle; either it went both ways around the quasar or only one way. Actually, Wheeler says, quantum phenomena are neither waves nor particles but are intrinsically undefined until the moment they are measured. In a sense, the British philosopher Bishop Berkeley was right when he asserted two centuries ago that "to be is to be perceived."

Reflecting on quantum mechanics some 60 years ago, the British physicist Sir Arthur Eddington complained that the theory made as much sense as Lewis Carroll's poem "Jabberwocky," in which "slithy toves did gyre and gimble in the wabe." Unfortunately, the jargon of quantum mechanics is rather less lively. An unobserved quantum entity is said to exist in a "coherent superposition" of all the possible "states" permitted by its "wave function." But as soon as an observer makes a measurement capable of distinguishing between these states, the wave function "collapses," and the entity is forced into a single state.

Yet even this deliberately abstract language contains some misleading implications. One is that measurement requires direct physical intervention. Physicists often explain the uncertainty principle in this way: in measuring the position of a quantum entity, one inevitably knocks it off its course, losing information about its direction and about its phase, the relative position of its crests and troughs.

Most experiments do in fact involve intrusive measurements. For example, blocking one path or the other or moving detectors close to the slits obviously disturbs the photons' passage in the two-slit experiments, as does placing a detector along one route of the delayed-choice experiment. But an experiment done last year by Mandel's team at the University of Rochester shows that a photon can be forced to switch from wavelike to particlelike behavior by something much more subtle than direct intervention.

The experiment relies on a parametric down-converter, an unusual lens that splits a photon of a given energy into two photons whose energy is half as great. Although the device was developed in the 1960s, the Rochester group pioneered its use in tests of quantum mechanics. In the experiment, a laser fires light at a beam splitter. Reflected photons are directed to one down-converter, and transmitted photons go to another down-converter. Each down-converter splits any photon impinging on it into two lower-frequency photons, one called the signal and the other called the idler. The two down-converters are arranged so that the two idler beams merge into a single beam. Mirrors steer the overlapping idlers to one detector and the two signal beams to a separate detector.

This design does not permit an observer to tell which way any single photon went after encountering the beam splitter. Each photon therefore goes both right and left at the beam splitter, like a wave, and passes through both down-converters, producing two signal wavelets and two idler wavelets. The sig-

LEONARD MANDEL (*at left*) and co-workers at the University of Rochester gather around a parametric down-converter, an unusual crystal that converts any photon striking it into two photons with half as much energy. Mandel's group pioneered the use of the device in tests of quantum mechanics.

nal wavelets generate an interference pattern at their detector. The pattern is revealed by gradually lengthening the distance that signals from one down-converter must go to reach the detector. The rate of detection then rises and falls as the crests and troughs of the interfering wavelets shift in relation to each other, going in and out of phase.

Now comes the odd part. The signal photons and the idler photons, once emitted by the down-converters, never again cross paths; they proceed to their respective detectors independently of each other. Nevertheless, simply by blocking the path of one set of idler photons, the researchers destroy the interference pattern of the signal photons. What has changed?

The answer is that the observer's potential knowledge has changed. He can now determine which route the signal photons took to their detector by comparing their arrival times with those of the remaining, unblocked idlers. The original photon can no longer go both ways at the beam splitter, like a wave, but must either bounce off or pass through, like a particle.

The comparison of arrival times need not actually be performed to destroy the interference pattern. The mere "threat" of obtaining information about which way the photon traveled, Mandel explains, forces it to travel only one route. "The quantum state reflects not only what we know about the system but what is in principle knowable," Mandel says.

Can the threat of obtaining incriminating information, once made, be retracted? In other words, are measurements reversible? Many theorists, including Bohr, thought not, and the phrase "collapse of the wave function" reflects that belief. But since 1983 Marlan O. Scully, a theorist at the University of New Mexico, has argued that it should be possible to gain information about the state of a quantum phenomenon, thereby destroying its wavelike properties, and then restore those properties by "erasing" the information.

Several groups working with optical interferometry, including Mandel's, claim to have demonstrated what Scully has dubbed a "quantum eraser." The group that has come closest, according to Scully, is one led by Raymond Y. Chiao of the University of California at Berkeley.

Earlier this year Chiao's group passed a beam of light through a down-conversion crystal, generating two identical photons. After being directed by mirrors along separate paths, the two photons crossed paths again at a half-silvered mirror and then entered two detectors. Because it was impossible to know which photon ended up in which detector, each photon seemed to go both ways. As in Mandel's experiment, the interference pattern was revealed by lengthening one arm of the interferometer; a device called a coincidence counter showed the simultaneous firings of the two photon detectors rising and falling as the two wavelets entering each detector went in and out of phase.

Then the workers added a device to the interferometer that shifted the polarization of one set of photons by 90 degrees. If one thinks of a ray of light as an arrow, polarization is the orientation of the plane of the arrowhead. One of the peculiarities of polarization is that it is a strictly binary property; photons are always polarized either vertically or horizontally. The altered polarization served as a tag; by putting polarization detectors in front of the simple light detectors at the end of the routes, one could determine which route each photon had taken. The two paths were no longer indistinguishable, and so the interference pattern disappeared.

Finally, Chiao's group inserted two devices that admitted only light polarized in one direction just in front of the detectors. The paths were indistinguishable again, and the interference pattern reappeared. Unlike Humpty-Dumpty, a collapsed wave function can be put back together again.

Spooky Action

Following up another proposal by Scully, Chiao has even suggested a way to delay the choice of whether or not to restore the interference pattern until *after* the photons have struck the detectors. The simple polarizing filters in front of the detectors are replaced with polarizing beam splitters, which direct photons with opposite polarization to different detectors. A computer then stores the data on the arrival times of all the photons in one file and the polarization of all the photons in another file. Viewed all at once without regard to polarization, the arrival times show no interference pattern. But if one separates differently polarized photons and plots them independently, two distinct interference patterns emerge.

Such possibilities provoke consternation in some quarters. Edwin T. Jaynes of Washington University, a prominent theorist whose work helped to inspire Scully to conceive the quantum eraser, has nonetheless dubbed it "medieval necromancy." Scully was so pleased by Jaynes's remark that he included it in a recent article on the quantum eraser.

Necromancy cannot hold a candle to nonlocality. Einstein, Boris Podolsky and Nathan Rosen first drew attention to this bizarre quantum property (which is now often called the EPR effect in their honor) in 1935 with a thought experiment designed to prove that quantum mechanics was hopelessly flawed. What would happen, Einstein and his colleagues asked, if a particle consisting of two protons decayed, sending the protons in opposite directions? According to quantum mechanics, as long as both protons remain unobserved their properties remain indefinite, in a superposition of all possible states; that means each one travels in all possible directions.

But because of their common origin, the properties of the protons are tightly correlated, or "entangled." For example, through simple conservation of momentum, one knows that if one proton heads north, the other must have headed south. Consequently, measuring the momentum of one proton instantaneously determines the momentum of the other proton—even if it has traveled to the opposite end of the universe. Einstein said that this "spooky action at a distance" was incompatible with any "realistic" model of reality; all the properties of each proton must be fixed from the moment they first fly apart.

Until the early 1960s, most physicists considered the issue entirely academic, since no one could imagine how to resolve it experimentally. Then, in 1964, John S. Bell of CERN, the European laboratory for particle physics, showed that quantum mechanics predicted stronger statistical correlations between entangled particles than the so-called local realistic theory that Einstein preferred. Bell's papers triggered a flurry of laboratory work, culminating in a classic (but not classical) experiment performed a decade ago by Alain Aspect of the University of Paris.

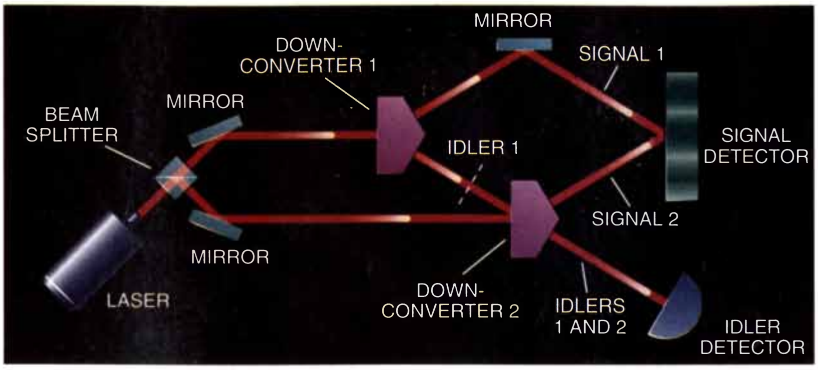
Instead of the momentum of protons, Aspect analyzed the polarization of pairs of photons emitted by a single source toward separate detectors. Measured independently, the polarization of each set of photons fluctuated in a seemingly random way. But when the two sets of measurements were compared, they displayed an agreement stronger than could be accounted for by any local realistic theory—just as Bell had predicted. Einstein's spooky action at a distance was real.

Until recently, no experiment had successfully shown that the EPR effect held true for momentum, as Einstein, Podolsky and Rosen had originally proposed. Two years ago John G. Rarity and Paul R. Tapster of the Royal Signals and Radar Establishment in England finally achieved that feat.

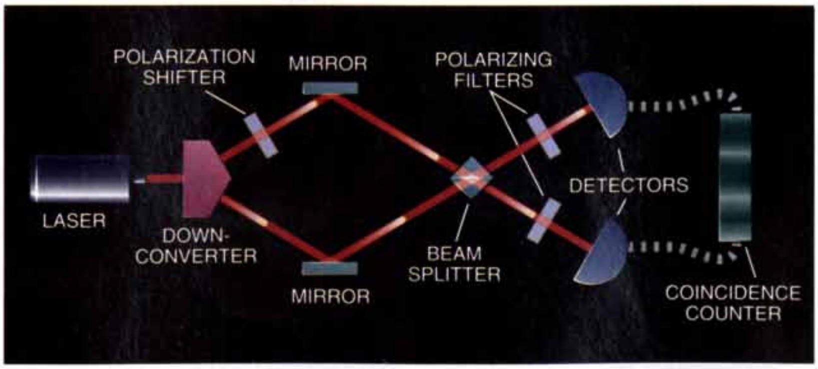
The experiment began with a laser firing into a down-converter, which produced pairs of correlated photons. Each of these photons then passed through a separate two-slit apparatus and thence to a photon detector. Through conservation of momentum, one could determine the route of each photon if one knew the route of its partner. But the arrangement of mirrors and beam splitters made it impossible to determine the actual route of either photon.

Next, the workers slightly lengthened one of the four routes, as Chiao did in his quantum eraser experiment. Although the rate at which photons struck each detector did not change, the rate of simultaneous firings recorded by a coincidence counter oscillated, forming a telltale interference pattern like the one

How to Destroy—and Revive—a Light Wave



Information rather than direct intervention destroys wavelike behavior in an experiment done at the University of Rochester. A laser fires photons past a half-silvered mirror, or beam splitter, to two down-converters, labeled 1 and 2. These convert each incident photon into two lower-energy photons, called signals and idlers. Because the signal detector cannot tell how the signals arrived, each signal takes both routes, like a wave, generating an interference pattern at the signal detector. But the pattern can be destroyed merely by blocking idlers from down-converter 1 (*dotted line*). The reason is that each signal's path can now be retraced; simultaneous detection of a signal and idler indicates that both came from a photon reflected by the beam splitter into down-converter 2.



Erasing information about the path of a photon restores wavelike behavior in an experiment done at the University of California at Berkeley. Pairs of identically polarized photons produced by a down-converter bounce off mirrors, converge again at a beam splitter and pass into two detectors. A coincidence counter observes an interference pattern in the rate of simultaneous detections by the two detectors, indicating that each photon has gone both ways at the beam splitter, like a wave. Adding a polarization shifter to one path destroys the pattern by making it possible to distinguish the photons. But placing two polarizing filters in front of the detectors makes the photons identical again, erasing the polarization distinction and restoring the interference pattern.

observed by Chiao. Such a pattern could occur only if each photon, the one on the left and the one on the right, was passing through both slits to its respective detector, its momentum fundamentally undefined and yet still correlated with the momentum of its distant partner.

Still more ambitious EPR experiments have been proposed but not yet carried out. Greenberger, Zeilinger and Michael Horne of Stonehill College have shown that three or more particles sprung from a single source will exhibit much stronger nonlocal correlations than those between just two particles. Bernard Yurke and David Stoler of AT&T Bell Laboratories have even suggested a way in which three particles emitted from separate locations can exhibit the EPR effect.

Unfortunately, the EPR effect does not provide a loophole in the theory of relativity, which prohibits communications faster than light, since each isolated observer of a correlated particle sees only an apparently random fluctuation of properties. But the effect does allow one safely to transmit a random number that can then serve as the numerical "key" for an encryption system. In fact, such a device has been built by Charles H. Bennett of the IBM Thomas J. Watson Research Center.

A die-hard realist might dismiss the experiments described above, since they all involve that quintessence of ineffability, light. But electrons, neutrons, protons and even whole atoms—the stuff our own bodies are made of—also display pathological behavior. Researchers observed wavelike behavior in electrons through indirect means as early as the 1920s, and they began carrying out two-slit experiments with electrons several decades ago.

Superposed Philosophers

A new round of electron experiments may be carried out soon if Yakir Aharonov of Tel-Aviv University has his way. Noting that superposition is generally inferred from observations of large numbers of particles, Aharonov contends that a single electron bound to a hydrogen atom could be detected smeared out in a relatively large cavity—say, 10 centimeters across—by very delicately scattering photons off it.

Aharonov has not yet published his idea—"I am a very fast thinker but a very slow writer," he says—and some physicists he has discussed it with are skeptical. On the other hand, many were skeptical in 1958, when Aharonov and David Bohm of the University of London suggested a way in which a magnetic field could influence an electron that, strictly speaking, lay completely beyond the field's range. The so-called Aharonov-Bohm effect has now been confirmed in laboratories.

Since the mid-1970s various workers have done interference experiments with neutrons, which are almost 2,000 times heavier than electrons. Some 15 years ago, for example, Samuel A. Werner of the University of Missouri at Columbia and others found that the interference pattern formed by neutrons diffracted along two paths by a sculpted silicon crystal could be altered simply by changing the interferometer's orientation relative to the earth's gravitational field. It was the first demonstration that the Schrödinger equation holds true under the sway of gravity.

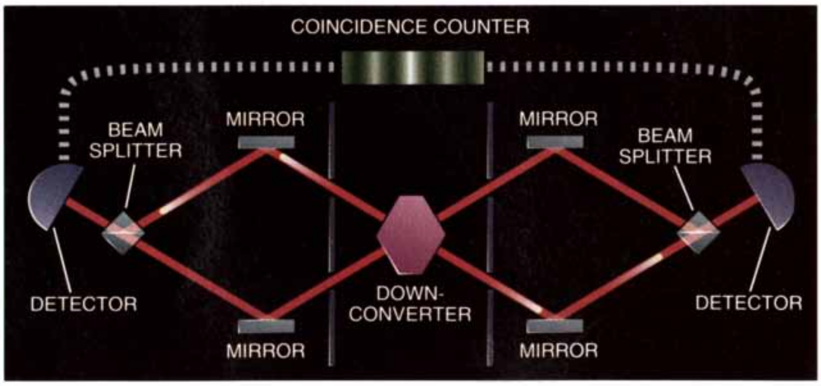
Investigators have begun doing interferometry with whole atoms only in the past few years. Such experiments are extraordinarily difficult. Atoms cannot pass through lenses or crystals, as photons, electrons and even neutrons can. Moreover, since the wavelength of an object is inversely proportional to its mass and velocity, the particle must move slowly for its wavelength to be detectable. Yet workers such as David E. Pritchard of the Massachusetts Institute of Technology have created the equivalent of beam splitters, mirrors and lenses for atoms out of metal plates with precisely machined grooves and even standing waves of light, formed when a wave of light reflects back on itself in such a way that its crests and troughs match precisely.

Pritchard says physicists may one day be able to pass biologically significant molecules such as proteins or nucleic acids through an interferometer. In principle, one could even observe wavelike behavior in a whole organism, such as an amoeba. There are some obstacles, though: the amoeba would have to travel very slowly, so slowly, in fact, that it would take some three years to get through the interferometer, according to Pritchard. The experiment would also have to be conducted in an environment completely free of gravitational or other influences—that is, in outer space.

Getting a slightly larger and more intelligent organism, for instance, a philosopher, to take two paths through a two-slit apparatus would be even trickier. "It would take longer than the age of the universe," Pritchard says.

While physicists may never nudge a philosopher into a superposition of states, they are hard at work trying to induce wavelike behavior in objects literally large enough to see. The research has rekindled interest in a famous thought experiment posed by Schrödinger in 1935. In a version altered by John Bell, the EPR theorist, to be more palatable to animal lovers, a cat is placed in a box containing a lump of radioactive matter, which has a 50 per-

How Distant Particles Keep in Touch



Spooky correlations between separate photons were demonstrated in an experiment at the Royal Signals and Radar Establishment in England. In this simplified depiction, a down-converter sends pairs of photons in opposite directions. Each photon passes through a separate two-slit apparatus and is directed by mirrors to a detector. Because the detectors cannot distinguish which slit a photon passes through, each photon goes both ways, generating an interference pattern in the coincidence counter. Yet each photon's direction, or momentum, is also correlated with its partner's. A measurement showing a photon going through the upper left slit would instantaneously force its distant partner to go through the lower slit on the right.

JOHN A. WHEELER, seen here with the likenesses of two earlier explorers of the quantum realm, Einstein and Bohr, thinks the deepest lesson of quantum mechanics may be that reality is defined by the questions we put to it.

cent chance of emitting a particle in a one-hour period. When the particle decays, it triggers a Geiger counter, which in turn causes a flask of milk to pour into a bowl, feeding the cat. (In Schrödinger's version, a hammer smashes a flask of poison gas, killing the cat.)

Common sense dictates that a cat cannot have a stomach both empty and full. But quantum mechanics dictates that after one hour, if no one has looked in the box, the radioactive lump and so the cat exist in a superposition of indistinguishable states; the former is both decayed and undecayed, and the latter is both hungry and full.

Various resolutions to the paradox have been suggested. Wojciech H. Zurek, a theorist at Los Alamos National Laboratory, contends that as a quantum phenomenon propagates, its interaction with the environment inevitably causes its superposed states to become distinguishable and thus to collapse into a single state. Mandel of the University of Rochester thinks this view is supported by his experiment, in which the mere potential for knowledge of a photon's path destroyed its interference pattern. After all, one can easily learn whether the cat has been fed—say, by making the box transparent—without actually disturbing it.

But since the early 1980s Anthony J. Leggett, a theorist at the University of Illinois, has argued that one should be able to observe a superconducting quantum interference device, more commonly called a SQUID, in a superposition of states. A SQUID, which is typically the size of a pinhead and therefore huge in comparison with atoms or other quantum objects, consists of a loop of superconducting material, through which electrons flow without resistance, broken by a thin slice of insulating material called a Josephson junction. In a classical world the electrons would be completely blocked by the insulator, but the quantum indefiniteness of the electrons' positions allows hordes of them to "tunnel" blithely through the gap.

Inspired by Leggett's calculations, Claudia D. Tesche of the IBM Watson center proposed an experiment that could show the superposition quite directly. Given certain conditions, Tesche notes, the current in a SQUID has an equal chance of flowing in either direction. According to quantum mechanics, then, it should flow both ways, creating an interference pattern analogous to the one formed in a two-slit experiment.

Tesche's design calls for placing two extremely sensitive switches around the SQUID, each of which is tripped when the current is going in a different direction. Of course, once a switch is tripped, the wave function collapses, and the interference pattern is destroyed. Tesche hopes to infer the pattern from those microseconds during which the switches are not activated—making measurements, in effect, by not making them.

Orthodoxy under Attack

Other theorists note that Tesche's experiment is extremely difficult, since even minute disturbances from the environment can cause the SQUID's wave function to collapse. In fact, Tesche recently turned to other, more conventional pursuits, at least temporarily setting aside the experiment. "It wasn't working very well," she concedes.

Yet less ambitious experiments by John Clarke of the University of California at Berkeley, Richard A. Webb of IBM and others have produced strong circumstantial evidence that a SQUID can in fact exist in a superposition of two states. The experiments involve a property known as flux, which is the area of the superconducting ring multiplied by the strength of the magnetic field perpendicular to the ring. In an ordinary superconducting ring the flux would be constant, but measurements with magnetometers show the flux of the SQUID spontaneously jumping from one value to another. Such jumps can occur only if the flux is in a superposition of states—hungry and full at the same time, as it were.

All the recent experiments, completed and proposed, have hardly led to a consensus on what exactly quantum mechanics means. If only by default, the "orthodox" view of quantum mechanics is still the one set forth in the 1920s by Bohr. Called the Copenhagen interpretation, its basic assertion is that what we observe is all we can know; any speculation about what a photon, an atom or even a SQUID "really is" or what it is doing when we're not looking is just that—speculation.

To be sure, the Copenhagen interpretation has come under attack from theorists in recent years, most notably from John Bell, author of the brilliant proof of the divergence between "realistic" and quantum predictions for EPR experiments. In a television interview just before his sudden death from a stroke two years ago, the Irish physicist expressed his dissatisfaction with the Copenhagen interpretation, noting that it "says we must accept meaninglessness." Does that make you afraid? the interviewer asked. "No, just disgusted," Bell replied, smiling.

Bell's exhortations helped to revive interest in a realistic theory originally proposed in the 1950s by Bohm. In Bohm's view, a quantum entity such as an electron does in fact exist in a particular place at a particular time, but its behavior is governed by an unusual field, or pilot wave, whose properties are defined by the Schrödinger wave function. The hypothesis does allow one quantum quirk, nonlocality, but it eliminates another, the indefiniteness of position of a particle. Its predictions are identical to those of standard quantum mechanics.

Bell also boosted the standing of a theory developed six years ago by GianCarlo Ghirardi and Tullio Weber of the University of Trieste and Alberto Rimini of the University of Pavia and refined more recently by Philip Pearle of Hamilton College. By adding a nonlinear term to the Schrödinger equation, the theory causes superposed states of a system to converge into a single state as the system approaches macroscopic dimensions, thereby eliminating the Schrödinger's cat paradox, among other embarrassments.

Unlike Bohm's pilot-wave concept, the theory of Ghirardi's group offers predictions that diverge from those of orthodox quantum physics, albeit subtly. "If you shine a neutron through two slits, you get an interference pattern," Pearle says. "But if our theory is correct, the interference should disappear if you make the measurement far enough away." The theory also requires slight violations of the law of conservation of energy. Zeilinger of the University of Innsbruck was sufficiently interested in the theory to test the neutron prediction, which was not borne out. "This approach is one of those dead-end roads that has to be walked by someone," he sighs.

Yet another view currently enjoying some attention, although not as a result of Bell's efforts, is the many-worlds interpretation, which was invented in the 1950s by Hugh Everett III of Princeton. The theory sought to answer the question of why, when we observe a quantum phenomenon, we see only one outcome of the many allowed by its wave function. Everett proposed that whenever a measurement forces a particle to make a choice, for instance, between going left or right in a two-slit apparatus, the entire universe splits into two separate universes; the particle goes left in one universe and right in the other.

Although the theory was long dismissed as more science fiction than science, it has been revived in a modified form by Murray Gell-Mann of the California Institute of Technology and James B. Hartle of the University of California at Santa Barbara. They call their version the many-histories interpretation and emphasize that the histories are "potentialities" rather than physical actualities. Gell-Mann has reportedly predicted that this view will dominate the field by the end of the century.

An intriguing alternative, called the many-minds view, has been advanced by David Z. Albert, a physicist-turned-philosopher at Columbia University, and Barry Loewer, a philosopher from Rutgers University. Each observer, they explain, or "sentient physical system," is associated with an infinite set of minds, which experience different possible outcomes of any quantum measurement. The array of choices embedded in the Schrödinger equation corresponds to the myriad experiences undergone by these minds rather than to an infinitude of universes. The concept may sound far-fetched, but it is no more radical, Albert argues, than the many-histories theory or even the Copenhagen interpretation itself.

The It from Bit

Other philosophers call for a sea change in our very modes of thought. After Einstein introduced his theory of relativity, notes Jeffrey Bub, a philosopher at the University of Maryland, "we threw out the old Euclidean notion of space and time, and now we have a more generalized notion." Quantum theory may demand a similar revamping of our concepts of rationality and logic, Bub says. Boolean logic, which is based on either-or propositions, suffices for a world in which an atom goes either through one slit or the other, but not both slits. "Quantum mechanical logic is non-Boolean," he comments. "Once you understand that, it may make sense." Bub concedes, however, that none of the so-called quantum logic systems devised so far has proved very convincing.

A different kind of paradigm shift is envisioned by Wheeler. The most profound lesson of quantum mechanics, he remarks, is that physical phenomena are somehow defined by the questions we ask of them. "This is in some sense a participatory universe," he says. The basis of reality may not be the quantum, which despite its elusiveness is still a physical phenomenon, but the bit, the answer to a yes-or-no question, which is the fundamental currency of computing and communications. Wheeler calls his idea "the it from bit."

Following Wheeler's lead, various theorists are trying to recast quantum physics in terms of information theory, which was developed 44 years ago to maximize the amount of information transmitted over communications channels. Already these investigators have found that Heisenberg's uncertainty principle, wave-particle duality and nonlocality can be formulated more powerfully in the context of information theory, according to William K. Wootters of Williams College, a former Wheeler student who is pursuing the it-from-bit concept.

Meanwhile theorists at the surreal frontier of quantum theory are conjuring up thought experiments that could unveil the riddle in the enigma once and for all. David Deutsch of the University of Oxford thinks it should be possible, at least in principle, to build a "quantum computer," one that achieves superposition of states. Deutsch has shown that if different superposed states of the computer can work on separate parts of a problem at the same time, the computer may achieve a kind of quantum parallelism, solving certain problems more quickly than classical computers.

Taking this idea further, Albert—with just one of his minds—has conceived of a quantum computer capable of making certain measurements of itself and its environment. Such a "quantum automaton" would be capable of knowing more about itself than any outside observer could ever know—and even more than is ordinarily permitted by the uncertainty principle. The automaton could also serve as a kind of eyewitness of the quantum world, resolving questions about whether wave functions truly collapse, for example. Albert says he has no idea how actually to engineer such a machine, but his calculations show the Schrödinger equation allows such a possibility.

If that doesn't work, there is always Aharonov's time machine. The machine, which is based not only on quantum theory but also on general relativity, is a massive sphere that can rapidly expand or contract. Einstein's theory predicts that time will speed up for an occupant of the sphere as it expands and gravity becomes proportionately weaker, and time will slow down as the sphere contracts. If the machine and its occupant can be induced into a superposition of states corresponding to different sizes and so different rates of time, Aharonov says, they may "tunnel" into the future. The occupant can then disembark, ask physicists of the future to explain the mysteries of quantum mechanics and then bring the answers—assuming there are any—back to the present. Until then, like Plato's benighted cave dwellers, we can only stare at the shadows of quanta flickering on the walls of our cave and wonder what they mean.