Faster than Light?

Experiments in quantum optics show that two distant events can influence each other faster than any signal could have traveled between them

by Raymond Y. Chiao, Paul G. Kwiat and Aephraim M. Steinberg

For experimentalists studying quantum mechanics, the fantastic often turns into reality. A recent example emerges from the study of a phenomenon known as nonlocality, or "action at a distance." This concept calls into question one of the most fundamental tenets of modern physics, the proposition that nothing travels faster than the speed of light.

An apparent violation of this proposition occurs when a particle at a wall vanishes, only to reappear—almost instantaneously—on the other side. A reference to Lewis Carroll may help here. When Alice stepped through the looking glass, her movement constituted in some sense action at a distance, or nonlocality: her effortless passage through a solid object was instantaneous. The particle's behavior is equally odd. If we attempted to calculate the particle's average velocity, we would find that it exceeded the speed of light.

Is this possible? Can one of the most famous laws of modern physics be breached with impunity? Or is there something wrong with our conception of quantum mechanics or with the idea of a "traversal velocity"? To answer such questions, we and several other workers have recently conducted many optical experiments to investigate some of the manifestations of quantum nonlocality. In particular, we focus on three demonstrations of nonlocal effects. In the first example, we "race" two photons, one of which must move through a "wall." In the second instance, we look at how the race is timed, showing that each photon travels along the two different race paths simultaneously. The final experiment reveals how the simultaneous behavior of photon twins is coupled, even if the twins are so far apart that no signal has time to travel between them.

The distinction between locality and nonlocality is related to the concept of a trajectory. For example, in the classical world a rolling croquet ball has a definite position at every moment. If each moment is captured as a snapshot and the pictures are joined, they form a smooth, unbroken line, or trajectory, from the player's mallet to the hoop. At each point on this trajectory, the croquet ball has a definite speed, which is related to its kinetic energy. If it travels on a flat pitch, it rolls to its target. But if the ball begins to roll up a hill, its kinetic energy is converted into potential energy. As a result, it slows—eventually to stop and roll back down. In the jargon of physics such a hill is called a barrier, because the ball does not have enough energy to travel over it, and, classically, it always rolls back. Similarly, if Alice were unable to hit croquet balls (or rolled-up hedgehogs, as Carroll would have them) with enough energy to send them crashing through a brick wall, they would merely bounce off.

According to quantum mechanics, this concept of a trajectory is flawed. The position of a quantum mechanical particle, unlike that of a croquet ball, is not described as a precise mathematical point. Rather the particle is best represented as a smeared-out wave packet. This packet can be seen as resembling the shell of a tortoise, because it rises from its leading edge to a certain height and then slopes down again to its trailing edge. The height of the wave at a given position along this span indicates the probability that the particle occupies that position: the higher a given part of the wave packet, the more likely the particle is located there. The width of the packet from front to back represents the intrinsic uncertainty of the particle's location [*see box on page 57*]. When the particle is detected at one point, however, the entire wave packet disappears. Quantum mechanics does not tell us where the particle has been before this moment.

This uncertainty in location leads to one of the most remarkable consequences of quantum mechanics. If the hedgehogs are quantum mechanical, then the uncertainty of position permits the beasts to have a very small but perfectly real chance of appearing on the far side of the wall. This process is known as tunneling and plays a major role in science and technology. Tunneling is of central importance in nuclear fusion, certain high-speed electronic devices, the highest-resolution microscopes in existence and some theories of cosmology.

In spite of the name "tunneling," the barrier is intact at all times. In fact, if a particle were inside the barrier, its kinetic energy would be negative. Velocity is proportional to the square root of the kinetic energy, and so in the tunneling case one must take the square

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root of a negative number. Hence, it is impossible to ascribe a real velocity to the particle in the barrier. This is why when looking at the watch it has borrowed from the White Rabbit, the hedgehog that has tunneled to the far side of the wall wears—like most physicists since the 1930s—a puzzled expression. What time does the hedgehog see? In other words, how long did it take to tunnel through the barrier?

Over the years, many attempts have been made to answer the question of the tunneling time, but none has been universally accepted. Using photons rather than hedgehogs, our group has recently completed an experiment that provides one concrete definition of this time.

Photons are the elementary particles from which all light is made; a typical light bulb emits more than 100 billion such particles in one billionth of a second. Our experiment does not need nearly so many of them. To make our measurements, we used a light source that emits a pair of photons simultaneously. Each photon travels toward a different detector. A barrier is placed in the path of one of these photons, whereas the other is allowed to fly unimpeded. Most of the time, the first photon bounces off the barrier and is lost; only its twin is detected. Occasionally, however, the first photon tunnels through the barrier, and both photons reach their respective detectors. In this situation, we can compare their arrival times and thus see how long the tunneling process took.

The role of the barrier was played by a common optical element: a mirror. This mirror, however, is unlike the ordinary household variety (which relies on metallic coating and absorbs as much as 15 percent of the incident light). The laboratory mirrors consist of thin, alternating layers of two different types of transparent glass, through which light travels at slightly different speeds. These layers act as periodic "speed bumps." Individually, they would do little more than slow the light down. But when taken together and spaced appropriately, they form a region in which light finds it essentially impossible to travel. A multilayer coating one micron thick—one one-hundredth of the diameter of a typical human hair—reflects 99 percent of incident light at the photon energy (or, equivalently, the color of the light) for which it is designed. Our experiment looks at the remaining 1 percent of the photons, which tunnel through this looking glass.

During several days of data collection, more than one million photons tunneled through the barrier, one by one. We compared the arrival times for tunneling photons and for photons that had been traveling unimpeded at the speed of light. (The speed of light is so great that conventional electronics are hundreds of thousands of times too slow to perform the timing; the technique we used will be described later, as a second example of quantum nonlocality.)

The surprising result: on average, the tunneling photons arrived before those that traveled through air, implying an average tunneling velocity of about 1.7 times that of light. The result appears to contradict the classical notion of causality, because, according to Einstein's theory of relativity, no signal can travel faster than the speed of light. If signals

"TUNNELING" ALICE moves effortlessly through a mirror, much as photons do in experiments in quantum optics. Although he was not a physicist, Lewis Carroll almost seems to have anticipated a thorny 20th-century physics problem—that of the tunneling time—when he had Sir John Tenniel draw a strange face on the looking-glass clock.

LOOKING-GLASS CROQUET has Alice hitting rolled-up hedgehogs, each bearing an uncanny resemblance to a young Werner Heisenberg, toward a wall. Classically, the hedgehogs always bounce off. Quantum mechanically, however, a small probability exists that a hedgehog will appear on the far side. The puzzle facing quantum physicists: How long does it take

could move faster, effects could precede causes from the viewpoints of certain observers. For example, a light bulb might begin to glow before the switch was thrown.

The situation can be stated more precisely. If at some definite time you made a decision to start firing photons at a mirror by opening a starting gate, and someone else sat on the other side of the mirror looking for photons, how much time would elapse before the other person knew you had opened the gate? At first, it might seem that since the photon tunnels faster than light she would see the light before a signal traveling at the theoretical speed limit could have reached her, in violation of the Einsteinian view of causality. Such a state of affairs seems to suggest an array of extraordinary, even bizarre communication technologies. Indeed, the implications of faster-than-light influences led some physicists in the early part of the century to propose alternatives to the standard interpretation of quantum mechanics.

Is there a quantum mechanical way out of this paradox? Yes, there is, although it deprives us of the exciting possibility of toying with cause and effect. Until now, we have been talking about the tunneling velocity of photons in a classical context, as if it were a directly observable quantity. The Heisenberg uncertainty principle, however, indicates that it is not. The time of emission of a photon is not precisely defined, so neither is its exact location or velocity. In truth, the position of a photon is more correctly described by a bell-shaped probability distribution—our tortoise shell—whose width corresponds to the uncertainty of its location.

A relapse into metaphor might help to explain the point. The nose of each tortoise leaves the starting gate the instant of opening. The emergence of the nose marks the earliest time at which there is any possibility for observing a photon. No signal can ever be received before the nose arrives. But because of the uncertainty of the photon's location, on average a short delay exists before the photon crosses the gate. Most of the tortoise (where the photon is more likely to be detected) trails behind its nose.

For simplicity, we label the probability distribution of the photon that travels unimpeded to the detector as "tortoise 1" and that of the photon that tunnels as "tortoise 2." When tortoise 2 reaches the tunnel barrier, it splits into two smaller tortoises: one that is reflected back toward the start and one that crosses the barrier. These two partial tortoises together represent the probability distribution of a single photon. When the photon is detected at one position, its other partial tortoise instantly disappears. The reflected tortoise is bigger than the tunneling tortoise simply because the chances of reflection are greater than that of transmission (recall that the mirror reflects a photon 99 percent of the time).

We observe that the peak of tortoise 2's shell, representing the most likely position of the tunneling photon, reaches the finish line before the peak of tortoise 1's shell. But tortoise 2's nose arrives no earlier than the nose of tortoise 1. Because the tortoises' noses travel at the speed of light, the photon that signals the opening of the starting gate can never arrive earlier than the time allowed by causality [*see illustration on opposite page*].

In a typical experiment, however, the nose represents a region of such low probability that a photon is rarely observed there. The whereabouts of the photon, detected only once, are best predicted by the location of the peak. So even though the tortoises are nose and nose at the finish, the peak of tor-

to go through the wall? Does the traversal time violate Albert Einstein's famous speed limit?

toise 2's shell precedes that of tortoise 1's (remember, the transmitted tortoise is smaller than tortoise 1). A photon tunneling through the barrier is therefore most likely to arrive before a photon traveling unimpeded at the speed of light. Our experiment confirmed this prediction.

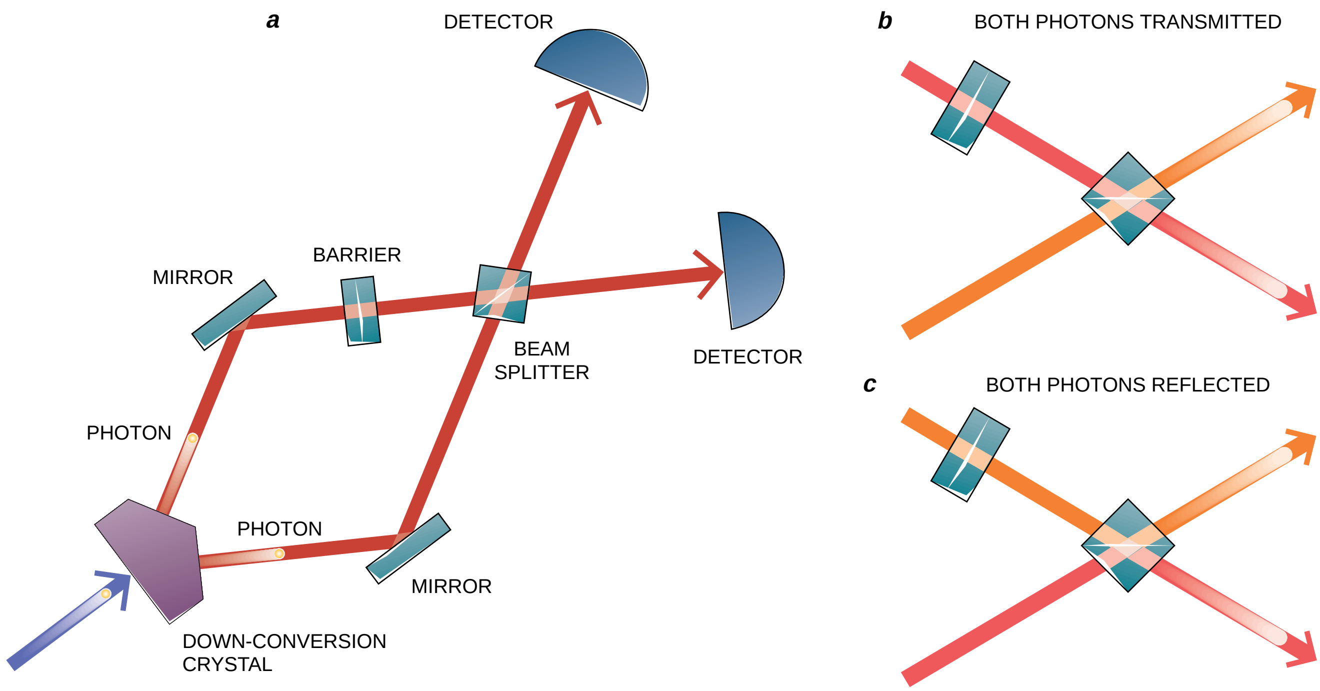
But we do not believe that any individual part of the wave packet moves faster than light. Rather the wave packet gets "reshaped" as it travels, until the peak that emerges consists primarily of what was originally in front. At no point does the tunneling-photon wave packet travel faster than the free-traveling photon. In 1982 Steven Chu of Stanford University and Stephen Wong, then at AT&T Bell Laboratories, observed a similar reshaping effect. They experimented with laser pulses consisting of many photons and found that the few photons that made it through an obstacle arrived sooner than those that could move freely. One might suppose that only the first few photons of each pulse were "allowed" through and thus dismiss the reshaping effect. But this interpretation is not possible in our case, because we study one photon at a time. At the moment of detection, the entire photon "jumps" instantly into the transmitted portion of the wave packet, beating its twin to the finish more than half the time.

Although reshaping seems to account for our observations, the question still lingers as to why reshaping should occur in the first place. No one yet has any physical explanation for the rapid tunneling. In fact, the question had puzzled investigators as early as the 1930s, when physicists such as Eugene Wigner of Princeton University had noticed that quantum theory seemed to imply such high tunneling speeds. Some assumed that approximations used in that prediction must be incorrect, whereas others held that the theory was correct but required cautious interpretation. Some researchers, in particular Markus Büttiker and Rolf Landauer of the IBM Thomas J. Watson Research Center, suggest that quantities other than the arrival time of the wave packet's peak (for example, the angle through which a "spinning" particle rotates while tunneling) might be more appropriate for describing the time "spent" inside the barrier. Although quantum mechanics can predict a particle's average arrival time, it lacks the classical notion of trajectories, without which the meaning of time spent in a region is unclear.

One hint to explain fast tunneling time stems from a peculiar characteristic of the phenomenon. According to theory, an increase in the width of the barrier does not lengthen the time needed by the wave packet to tunnel through. This observation can be roughly understood using the uncertainty principle. Specifically, the less time we spend studying a photon, the less certain we can be of its energy. Even if a photon fired at a barrier does not have enough energy to cross it, in some sense a short period initially exists during which the particle's energy is uncertain. During this time, it is as though the photon could temporarily borrow enough extra energy to make it across the barrier. The length of this grace period depends only on the borrowed energy, not on the width of the barrier. No matter how wide the barrier becomes, the transit time across it remains the same. For a sufficiently wide barrier, the apparent traversal speed would exceed the speed of light.

Obviously, for our measurements to be meaningful, our tortoises had to run exactly the same distance. In essence, we had to straighten the racetrack so that neither tortoise had the advantage of the inside lane. Then, when we placed a barrier in one path, any delay or acceleration would be attributed solely to quantum tunneling. One way to set up two equal lanes would be to determine how much time

RACING TORTOISES help to characterize tunneling time. Each represents the probability distribution of the position of a photon. The peak is where a photon is most likely to be detected. The tortoises start together (*left*). Tortoise 2 encounters a barrier and splits in two (*right*). Because the chance of tunneling is low, the transmitted tortoise is small, whereas the reflected one is nearly as tall as the original. On those rare occasions of tunneling, the peak of tortoise 2's shell on average crosses the finish line first—implying an average tunneling velocity of 1.7 times the speed of light. But the tunneling tortoise's nose never travels faster then light—note that both tortoises remain "nose and nose" at the end. Hence, Einstein's law is not violated.



TWIN-PHOTON INTERFEROMETER (*a*) precisely times racing photons. The photons are born in a down-conversion crystal and are directed by mirrors to a beam splitter. If one photon beats the other to the beam splitter (because of the barrier), both detectors will be triggered in about half the races. Two possibilities lead to such coincidence detections: both photons are transmitted by the beam splitter (*b*), or both are reflected (*c*). Aside from their arrival times, there is no way of determining which photon took which route; either could have traversed the barrier. (This nonlocality actually sustains the performance of the interferometer.) If both photons reach the beam splitter simultaneously, for quantum reasons they will head in the same direction, so that both detectors do not go off. The two possibilities shown are then said to interfere destructively.

it takes for a photon to travel from the source to the detector for each path. Once the times were equal, we would know the paths were also equal.

But performing such a measurement with a conventional stopwatch would require one whose hands went around nearly a billion billion times per minute. Fortunately, Leonard Mandel and his co-workers at the University of Rochester have developed an interference technique that can time our photons.

Mandel's quantum stopwatch relies on an optical element called a beam splitter [*see illustration above*]. Such a device transmits half the photons striking it and reflects the other half. The racetrack is set up so that two photon wave packets are released at the same time from the starting gate and approach the beam splitter from opposite sides. For each pair of photons, there are four possibilities: both photons might pass through the beam splitter; both might rebound from the beam splitter; both could go off together to one side; or both could go off together to the other side. The first two possibilities—that both photons are transmitted or both reflected—result in what are termed coincidence detections. Each photon reaches a different detector (placed on either side of the beam splitter), and both detectors are triggered within a billionth of a second of each other. Unfortunately, this time resolution is about how long the photons take to run the entire race and hence is much too coarse to be useful.

So how do the beam splitter and the detectors help in the setup of the racetrack? We simply tinker with the length of one of the paths until all coincidence detections disappear. By doing so, we make the photons reach the beam splitter at the same time, effectively rendering the two racing lanes equal. Admittedly, the proposition sounds peculiar—after all, equal path lengths would seem to imply coincident arrivals at the two detectors. Why would the absence of such events be the desired signal?

The reason lies in the way quantum mechanical particles interact with one another. All particles in nature are either bosons or fermions. Identical fermions (electrons, for example) obey the Pauli exclusion principle, which prevents any two of them from ever being in the same place at the same time. In contrast, bosons (such as photons) like being together. Thus, after reaching the beam splitter at the same time, the two photons prefer to head in the same direction. This preference leads to the detection of fewer coincidences (none, in an ideal experiment) than would be the case if the photons acted independently or arrived at the beam splitter at different times.

Therefore, to make sure the photons are in a fair race, we adjust one of the path lengths. As we do this, the rate of coincident detections goes through a dip whose minimum occurs when the photons take exactly the same amount of time to reach the beam splitter. The width of the dip (which is the limiting factor in the resolution of our experiments) corresponds to the size of the photon wave packets—typically, about the distance light moves in a few hundredths of a trillionth of a second.

Only when we knew that the two path lengths were equal did we install the barrier and begin the race. We then found that the coincidence rates were no longer at a minimum, implying that one of the photons was reaching the beam splitter first. To restore the minimum, we had to lengthen the path taken by the tunneling photon. This correction indicates that photons take less time to cross a barrier than to travel in air.

Even though investigators designed racetracks for photons and a clever timekeeping device for the race, the competition still should have been difficult to conduct. The fact that the test could be carried out at all constitutes a second validation of the principle of nonlocality, if not for which precise timing of the race would have been impossible. To determine the emission time of a photon most precisely, one would obviously like the photon wave packets to be as short as possible. The uncertainty principle, however, states that the more accurately one determines the emission time of a photon, the more uncertainty one has to accept in knowing its energy, or color [*see box below*].

Because of the uncertainty principle, a fundamental trade-off should emerge in our experiments. The colors that make up a photon will disperse in any kind of glass, widening the wave packet and reducing the precision of the timing. Dispersion arises from the fact that different colors travel at various speeds in glass—blue light generally moves more slowly than red. A familiar example of dispersion is the splitting of white light into its constituent colors by a prism.

As a short pulse of light travels through a dispersive medium (the barrier itself or one of the glass elements used to steer the light), it spreads out into a "chirped" pulse: the redder part pulls ahead, and the bluer hues lag behind [*see illustration on next page*]. A simple calculation shows that the width of our photon pulses would quadruple on passage through an inch of glass. The presence of such broadening should have made it well nigh impossible to tell which tortoise crossed the finish line first. Remarkably, the widening of the photon pulse did not degrade the precision of our timing.

Herein lies our second example of quantum nonlocality. Essentially both twin photons must be traveling both paths simultaneously. Almost magically, potential timing errors cancel out as a result.

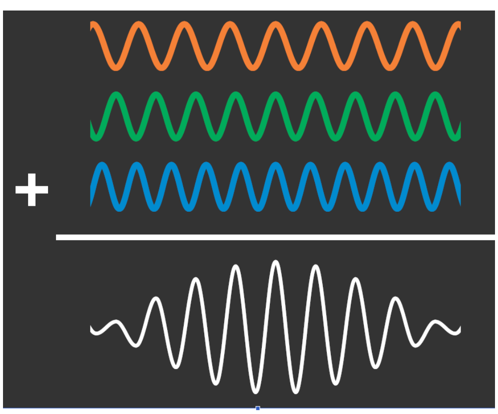
To understand this cancellation effect, we need to examine a special property of our photon pairs. The pairs are born in what physicists call "spontaneous parametric down-conversion." The process occurs when a photon travels into a crystal that has nonlinear optical properties. Such a crystal can absorb a single photon and emit a pair of other photons, each with about half the energy of the parent, in its place (this is the meaning of the phrase "down-conversion"). An ultraviolet photon, for instance, would produce two infrared ones. The two photons are emitted simultaneously, and the sum of their energies exactly equals the energy of the parent photon. In other words, the colors of the photon pairs are correlated—if one is slightly bluer (and thus travels more slowly in glass), then the other must be slightly redder (and must travel more quickly).

One might think that differences between siblings might affect the outcome of the race—one tortoise might be more athletic than the other. Yet because of nonlocality, any discrepancy between the pair proves irrelevant. The key point is that neither detector has any way of identifying which of the photons took which path. Either photon

Wave Packets

A good way to understand wave packets is to construct one, by adding together waves of different frequencies. We start with a central frequency (*denoted by the green curve*), a wave with no beginning and no end. If we now add two more waves of slightly lower and higher frequency (*orange and blue curves, respectively*), we obtain a pulselike object (*white curve*). When enough frequencies are added, a true pulse, or wave packet, can be formed, which is confined to a small region of space. If the range of frequencies used to make the pulse were decreased (for example, by using colors only from yellow to green, instead of from orange to blue), we would create a longer pulse. Conversely, if we had included all colors from red to violet, the packet could have been even shorter.

Mathematically speaking, if we use $\Delta\nu$ for the width of the range of colors and Δt for the duration of the pulse, then we can write



$$\Delta\nu\,\Delta t \geq 1/4\pi,$$

which simply expresses the fact that a wider color range is needed to make a shorter wave packet. It holds true for any kind of wave—light, sound, water and so on.

The phenomenon acquires new physical significance when one makes the identification of electromagnetic frequency, ν, with photon energy, E, via the Planck-Einstein relation $E = h\nu$, where h is Planck's constant. The particle aspect of quantum mechanics enters at this point. In other words, a photon's energy depends on its color. Red photons have about three fifths the energy of blue ones. The above mathematical expression can then be rewritten as

$$\Delta E\,\Delta t \geq h/4\pi.$$

Physicists have become so attached to this formula that they have named it: Heisenberg's uncertainty principle. (An analogous and perhaps more familiar version exists for position and momentum.) One consequence of this principle for the experiments described in the article is that it is strictly impossible, even with a perfect apparatus, to know precisely both the time of emission of a photon and its energy.

Although we arrived at the uncertainty principle by considering the construction of wave packets, its application is remarkably far more wide-reaching and its connotations far more general. We cannot overemphasize that the uncertainty is inherent in the laws of nature. It is not merely a result of inaccurate measuring devices in our laboratories. The uncertainty principle is what keeps electrons from falling into the atomic nucleus, ultimately limits the resolution of microscopes and, according to some astrophysical theories, was initially responsible for the nonuniform distribution of matter in the universe.

might have passed through the barrier.

Having two or more coexisting possibilities that lead to the same final outcome results in what is termed an interference effect. Here each photon takes both paths simultaneously, and these two possibilities interfere with each other. That is, the possibility that the photon that went through the glass was the redder (faster) one interferes with the possibility that it was the bluer (slower) one. As a result, the speed differences balance, and the effects of dispersion cancel out. The dispersive widening of the individual photon pulses is no longer a factor. If nature acted locally, we would have been hard-pressed to conduct any measurements. The only way to describe what happens is to say that each twin travels through both the path with the barrier and the free path, a situation that exemplifies nonlocality.

Thus far we have discussed two nonlocal results from our quantum experiments. The first is the measurement of tunneling time, which requires two photons to start a race at exactly the same time. The second is the dispersion cancellation effect, which relies on a precise correlation of the racing photons' energies. In other words, the photons are said to be correlated in energy (what they do) and in time (when they do it). Our final example of nonlocality is effectively a combination of the first two. Specifically, one photon "reacts" to what its twin does instantaneously, no matter how far apart they are.

Knowledgeable readers may protest at this point, claiming that the Heisenberg uncertainty principle forbids precise specification of both time and energy. And they would be right, for a single particle. For two particles, however, quantum mechanics allows us to define simultaneously the difference between their emission times and the sum of their energies, even though neither particle's time or energy is specified. This fact led Einstein, Boris Podolsky and Nathan Rosen to conclude that quantum mechanics is an incomplete theory. In 1935 they formulated a thought experiment to demonstrate what they believed to be the shortcomings of quantum mechanics.

If one believes quantum mechanics, the dissenting physicists pointed out, then any two particles produced by a process such as down-conversion are coupled. For example, suppose we measure the time of emission of one particle. Because of the tight time correlation between them, we could predict with certainty the emission time of the other particle, without ever disturbing it. We could also measure directly the energy of the second particle and then infer the energy of the first particle. Somehow we would have managed to determine precisely both the energy and the time of each particle—in effect, beating the uncertainty principle. How can we understand the correlations and resolve this paradox?

There are basically two options. The first is that there exists what Einstein called "spooklike actions at a distance" (*spukhafte Fernwirkungen*). In this scenario, the quantum mechanical description of particles is the whole story. No particular time or energy is associated with any photon until, for example, an energy measurement is made. At that point, only one energy is observed. Because the energies of the two photons sum to the definite energy of the parent photon, the previously undetermined energy of the twin photon, which we did not measure, must instantaneously jump to the value demanded by energy conservation. This nonlocal "collapse" would occur no matter how far away the second photon had traveled. The uncertainty principle is not violated, because we can specify only one variable or the other: the energy measurement disrupts the system, instantaneously introducing a new uncertainty in the time.

Of course, such a crazy, nonlocal model should not be accepted if a simpler way exists to understand the correlations. A more intuitive explanation is that the twin photons leave the source at definite, correlated times, carrying definite, correlated energies. The fact that quantum mechanics cannot specify these properties simultaneously would merely indicate that the theory is incomplete.

Einstein, Podolsky and Rosen advocated the latter explanation. To them, there was nothing at all nonlocal in the observed correlations between particle pairs, because the properties of each particle are determined at the moment of emission. Quantum mechanics was only correct as a probabilistic theory, a kind of photon sociology, and could not completely describe all individual particles. One might imagine that there exists an underlying theory that could predict the specific results of all possible measurements and show that particles act locally. Such a theory would be based on some hidden variable yet to be discovered. In 1964 John S. Bell of CERN, the European laboratory for particle physics near Geneva, established a theorem showing that all invocations of local, hidden variables give predictions different from those stated by quantum mechanics.

Since then, experimental results have supported the nonlocal (quantum mechanical) picture and contradicted the intuitive one of Einstein, Podolsky and Rosen. Much of the credit for the pioneering work belongs to the groups led by John Clauser of the University of California at Berkeley and Alain Aspect, now at the Institute of Optics in Orsay. In the 1970s and

DISPERSION of a light pulse occurs because each color travels at a different speed. A short light pulse passing through a piece of glass will broaden into a "chirped" wave packet: the redder colors pull ahead while the bluer hues lag behind.

early 1980s they examined the correlations between polarizations in photons. The more recent work of John G. Rarity and Paul R. Tapster of the Royal Signals and Radar Establishment in England explored correlations between the momentum of twin photons. Our group has taken the tests one step further. Following an idea proposed by James D. Franson of Johns Hopkins University in 1989, we have performed an experiment to determine whether some local hidden variable model, rather than quantum mechanics, can account for the energy and time correlations.

In our experiment, photon twins from our down-conversion crystal are separately sent to identical interferometers [*see illustration at right*]. Each interferometer is designed much like an interstate highway with an optional detour. A photon can take a short path, going directly from its source to its destination. Or it can take the longer, detour path (whose length we can adjust) by detouring through the rest station before continuing on its way.

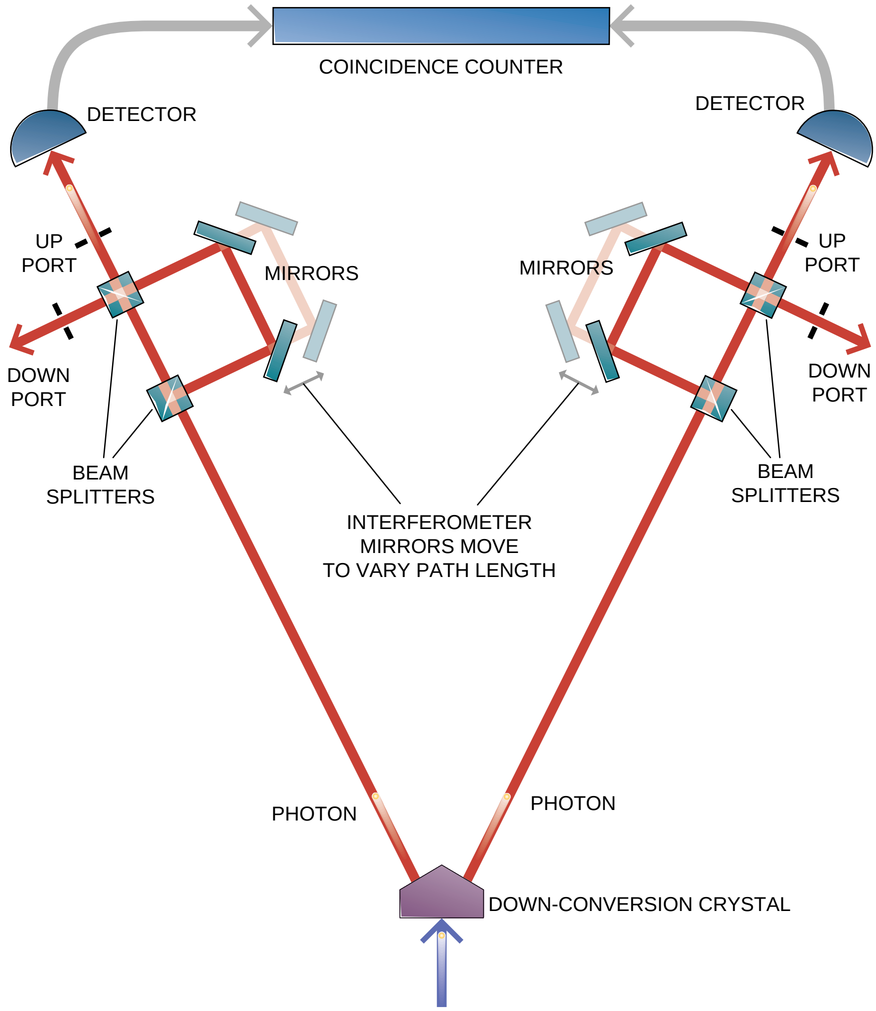
Now watch what happens when we send the members of a pair of photons through these interferometers. Each photon will randomly choose the long route (through the detour) or the shorter, direct route. After following one of the two paths, a photon can leave its interferometer through either of two ports, one labeled "up" and the other "down." We observed that each particle was as likely to leave through the up port as it was through the down. Thus, one might intuitively presume that the photon's choice of one exit would be unrelated to the exit choice its twin makes in the other interferometer. Wrong. Instead we see strong correlations between which way each photon goes when it leaves its interferometer. For certain detour lengths, for example, whenever the photon on the left leaves at the up exit, its twin on the right flies through its own up exit.

One might suspect that this correlation is built in from the start, as when one hides a white pawn in one fist and a black pawn in the other. Because their colors are well defined at the outset, we are not surprised that the instant we find a white pawn in one hand, we know with certainty that the other must be black.

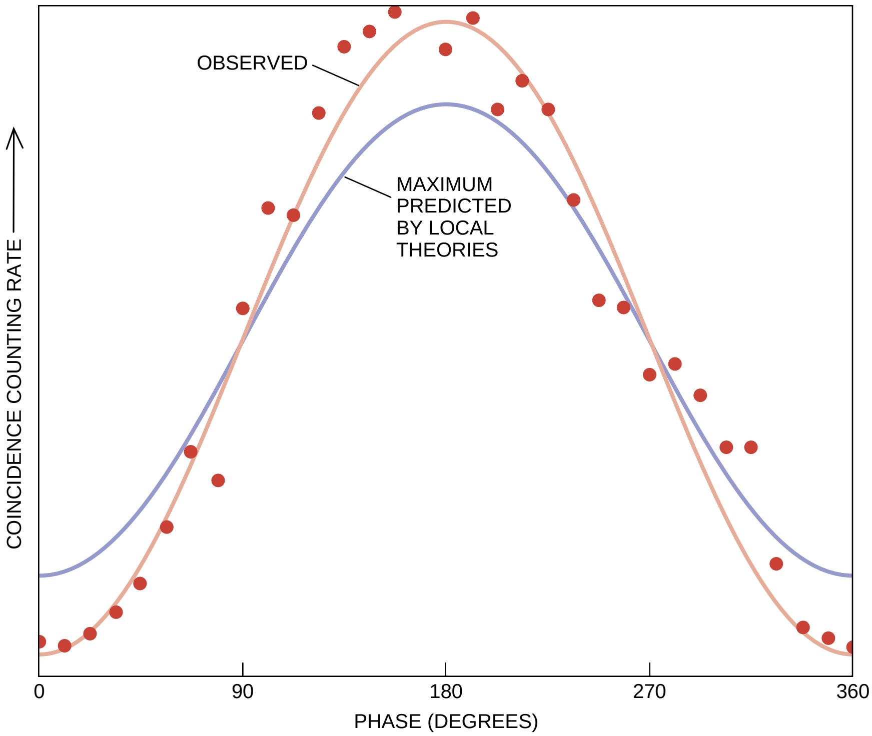
But a built-in correlation cannot account for the actual case in our experiment, which is much stranger: by changing the path length in either interferometer, we can control the nature of the correlations. We can go smoothly from a situation where the photons always exit the corresponding ports (both use the up port, or both use the down port) of their respective interferometers to one in which they always exit opposite ports. In principle, such a correlation would exist even if we adjusted the path length after the photons had left the source. In other words, before entering the interferometer, neither photon knows which way it is going to have to go—but on leaving, each one knows instantly (nonlocally) what its twin has done and behaves accordingly.

To analyze these correlations, we look at how often the photons emerge from each interferometer at the same time and yield a coincidence count between detectors placed at the up exit ports of the two interferometers. Varying either of the long-arm path lengths does not change the rate of detections at either detector individually. It does, however, affect the rate of coincidence counts, indicating the correlated behavior of each photon pair. This variation produces "fringes" reminiscent of the light and dark stripes in the traditional two-slit interferometer showing the wave nature of particles.

In our experiment, the fringes imply a peculiar interference effect. As alluded to earlier, interference can be expressed as the result of two or more indistinguishable, coexisting possibilities leading to the same final outcome (recall our second example of nonlocality, in which each photon travels along two different paths simultaneously, producing interference). In the present case, there are two possible ways for a coincidence count to occur: either both photons had to travel the short paths, or both photons had to travel the long paths. (In the cases in which one photon travels a short path and the other a long path, they arrive at different times and



NONLOCAL CORRELATION between two particles is demonstrated in the so-called Franson experiment, which sends two photons to separate but identical interferometers. Each photon may take a short route or a longer "detour" at the first beam splitter. They may leave through the upper or lower exit ports. A detector looks at the photons leaving the upper exit ports. Before entering its interferometer, neither photon knows which way it will go. After leaving, each knows instantly and nonlocally what its twin has done and so behaves accordingly.



RATE OF COINCIDENCES between left and right detectors in the Franson experiment (*red dots, with best-fit line*) strongly suggests nonlocality. The horizontal axis represents the sum of the two long path lengths, in angular units known as phases. The "contrast," or the degree of variation in these rates, exceeds the maximum allowed by local, realistic theories (*blue line*), implying that the correlations must be nonlocal, as shown by John S. Bell of CERN.

so do not interfere with each other; we discard these counts electronically.)

The coexistence of these two possibilities suggests a classically nonsensical picture. Because each photon arrives at the detector at the same time after having traveled both the long and short routes, each photon was emitted "twice"—once for the short path and once for the long path.

To see this, consider the analogy in which you play the role of one of the detectors. You receive a letter from a friend on another continent. You know the letter arrived via either an airplane or a boat, implying that it was mailed a week ago (by plane) or a month ago (by boat). For an interference effect to exist, the one letter had to have been mailed at both times. Classically, of course, this possibility is absurd. But in our experiments the observation of interference fringes implies that each of the twin photons possessed two indistinguishable times of emission from the crystal. Each photon has two birthdays.

More important, the exact form of the interference fringes can be used to differentiate between quantum mechanics and any conceivable local hidden variable theory (in which, for example, each photon might be born with a definite energy or already knowing which exit port to take). According to the constraints derived by Bell, no hidden variable theory can predict sinusoidal fringes that exhibit a "contrast" of greater than 71 percent—that is, the difference in intensity between light and dark stripes has a specific limit. Our data, however, display fringes that have a contrast of about 90 percent. If certain reasonable supplementary assumptions are made, one can conclude from these data that the intuitive, local, realistic picture suggested by Einstein and his cohorts is wrong: it is impossible to explain the observed results without acknowledging that the outcome of a measurement on the one side depends nonlocally on the result of a measurement on the other side.

So is Einstein's theory of relativity in danger? Astonishingly, no, because there is no way to use the correlations between particles to send a signal faster than light. The reason is that whether each photon reaches its detector or instead uses the down exit port is a random result. Only by comparing the apparently random records of counts at the two detectors, necessarily bringing our data together, can we notice the nonlocal correlations. The principles of causality remain inviolate.

Science-fiction buffs may be saddened to learn that faster-than-light communication still seems impossible. But several scientists have tried to make the best of the situation. They propose to use the randomness of the correlations for various cipher schemes. Codes produced by such quantum cryptography systems would be absolutely unbreakable [see "Quantum Cryptography," by Charles H. Bennett, Gilles Brassard and Artur D. Ekert; SCIENTIFIC AMERICAN, October 1992].

We have thus seen nonlocality in three different instances. First, in the process of tunneling, a photon is able to somehow sense the far side of a barrier and cross it in the same amount of time no matter how thick the barrier may be. Second, in the high-resolution timing experiments, the cancellation of dispersion depends on each of the two photons having traveled both paths in the interferometer. Finally, in the last experiment discussed, a nonlocal correlation of the energy and time between two photons is evidenced by the photons' coupled behavior after leaving the interferometers. Although in our experiments the photons were separated by only a few feet, quantum mechanics predicts that the correlations would have been observed no matter how far apart the two interferometers were.

Somehow nature has been clever enough to avoid any contradiction with the notion of causality. For in no way is it possible to use any of the above effects to send signals faster than the speed of light. The tenuous coexistence of relativity, which is local, and quantum mechanics, which is nonlocal, has weathered yet another storm.

FURTHER READING

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