# The Reality of the Quantum World

*Einstein held that quantum-mechanical descriptions of physical systems are incomplete. Laboratory tests show he was probably wrong; the bizarre nature of the quantum world must be accepted*

by Abner Shimony

We live in a remarkable era in which experimental results are beginning to elucidate philosophical questions. In no domain have the results been more dramatic than in quantum mechanics. The theory has been confirmed magnificently since the 1920's as its predictions of atomic, molecular, nuclear, optical, solid-state and elementary-particle phenomena were shown to be accurate. Yet in spite of these successes the bizarre and counterintuitive character of quantum mechanics has led some investigators, including Einstein, to believe quantum-mechanical descriptions of physical systems are incomplete and in need of supplementation. Recent experiments show that this opinion is very likely wrong. The experimental results reveal more clearly than ever that we live in a strange "quantum world" that defies comfortable, commonsense interpretation.

Here are a few of the new, strange findings we must begin to accept. First, two entities separated by many meters and possessing no mechanism for communicating with each other nonetheless can be "entangled": they can exhibit striking correlations in their behavior, so that a measurement done on one of the entities seems instantaneously to affect the result of a measurement on the other. The finding cannot be explained from a classical point of view, but it agrees completely with quantum mechanics. Second, a photon, the fundamental unit of light, can behave like either a particle or a wave, and it can exist in an ambiguous state until a measurement is made. If a particlelike property is measured, the photon behaves like a particle, and if a wavelike property is measured, the photon behaves like a wave. Whether the photon is wave- or particlelike is indefinite until the experimental arrangement is specified. Finally, the notion of indefiniteness is no longer confined to the atomic and subatomic domains. Investigators have found that a macroscopic system can under some circumstances exist in a state in which a macroscopic observable has an indefinite value. Each of these findings alters drastically the way we perceive the world.

An understanding of these experiments and their philosophical implications requires some familiarity with the basic ideas of quantum mechanics. Essential to any discussion of the theory is the concept of the quantum state, or wave function. The quantum state specifies all the quantities of a physical system to the extent that it is possible to do so. The caveat at the end of the preceding sentence is crucial, because according to quantum mechanics not all quantities of a system have simultaneously definite values. The familiar Heisenberg uncertainty principle, which asserts that the position and the momentum of a particle cannot be simultaneously definite, is perhaps the best-known instance of this proposition.

What the quantum state of a system does provide unequivocally is the probability of each possible outcome of every experiment that can be done on the system. If the probability is 1, the outcome is certain to occur; if the probability is zero, the outcome is certain not to occur. If, however, the probability is a number between zero and 1, then it cannot be said in any individual case what the outcome will be. All that can be said is what, on the average, the outcomes of a specified experiment carried out on a large number of replica systems will be.

Imagine, for instance, that measurements are made on a photon. The quantum state of the photon is fixed if three quantities are known: the photon's direction, its frequency and its linear polarization (the direction of the electric field associated with the photon). A suitable apparatus for measuring polarization is a sheet of polarizing film. The film is idealized so that it transmits all light incident on it at a right angle if the light is linearly polarized along a certain direction in the film called the transmission axis. The film blocks all light incident on it at a right angle if the light is linearly polarized perpendicular to the transmission axis.

Various experiments can be performed by rotating the polarizing film in different ways. If the photon is linearly polarized along the transmission axis, there is a probability of 1 that it will be transmitted. If the photon is linearly polarized perpendicular to the transmission axis, the probability that it will be transmitted is zero. A further implication of quantum mechanics, going beyond what has been said so far, is that if the photon is linearly polarized at some angle to the transmission axis between zero and 90 degrees, the probability of transmission is a number between zero and 1 (specifically, the square of the cosine of that particular angle). If the probability is, say, one-half, then out of 100 photons linearly polarized at the corresponding angle to the transmission axis 50 will be transmitted on the average.

Another basic idea of quantum mechanics is the superposition principle, which asserts that from any two quantum states of a system further states can be formed by superposing them. Physically the operation corresponds to forming a new state that "overlaps" each of the states from which it was formed. The concept can be illustrated by considering two quantum states of a photon in which the direction of the photon's polarization in the first state is perpendicular to the direction of the photon's polarization in the second. Then any number of states can be formed in which the photon's polarization points at some angle between the two perpendicular directions.

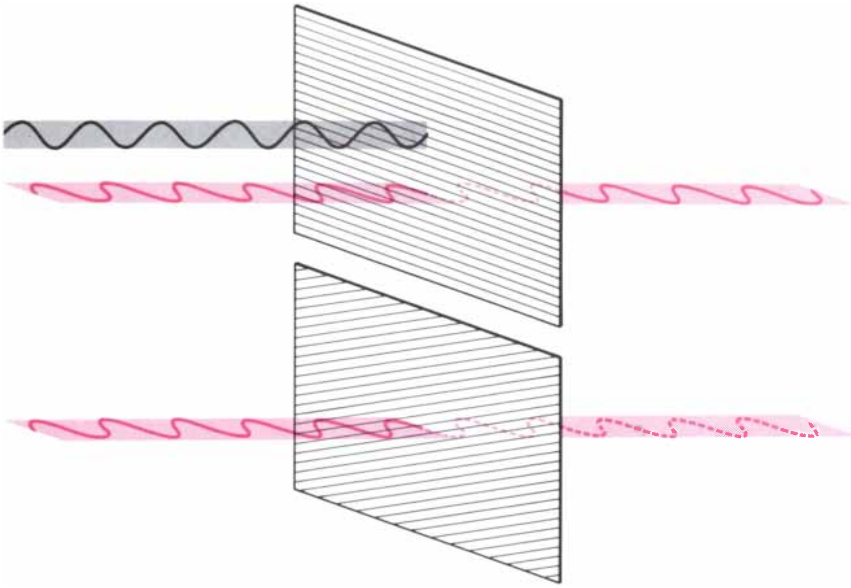
From these two basic ideas alone—indefiniteness and the superposition principle—it should be clear already that quantum mechanics conflicts sharply with common sense. If the quantum state of a system is a complete description of the system, then a quantity that has an indefinite value in that quantum state is objectively indefinite; its value is not merely unknown by the scientist who seeks to describe the system. Furthermore, since the outcome of a measurement of an objectively indefinite quantity is not determined by the quantum state, and yet the quantum state is the complete bearer of information about the system, the outcome is strictly a matter of objective chance—not just a matter of chance in the sense of unpredictability by the scientist. Finally, the probability of each possible outcome of the measurement is an objective probability. Classical physics did not conflict with common sense in these fundamental ways.

Even more startling implications flow from quantum mechanics if the system consists of two correlated parts. Suppose two photons fly apart in opposite directions. One possible quantum state of the pair of photons is the state in which both photons are linearly polarized along a vertical axis. Another possible state is the one in which they are both linearly polarized along a horizontal axis. There is nothing particularly bizarre or surprising about either of these two-photon quantum states, beyond the peculiarities of the single-photon states mentioned above. But if the superposition principle is brought into play, strange effects can occur.

In particular, by using the superposition principle one can form a quantum state that contains equal amounts of the vertically polarized state and the horizontally polarized state. This new state will figure prominently in what follows, and so it will be given a name, $\Psi_0$ (since the Greek letter psi is commonly used to represent a quantum state). The properties of $\Psi_0$ are most peculiar indeed. Imagine, for instance, inserting in the paths of the photons polarizing films with vertically oriented transmission axes. Because $\Psi_0$ contains equal amounts of the vertically and horizontally polarized states, there is a probability of one-half that both photons will be transmitted through their respective films and a probability of one-half that both will be blocked. What cannot happen is that one photon will be transmitted and the other will be blocked. In other words, the outcomes of the linear-polarization experiments on the two photons are strictly correlated.

The results will be the same if the polarizing films are oriented at an angle of 45 degrees with respect to

**EXPERIMENTAL TESTS are now shedding light on topics in quantum mechanics that were once confined to the realm of philosophical debate. In this experiment, which was done by Alain Aspect and his colleagues at the Institute of Optics of the University of Paris, the lasers at each side of the picture excite individual calcium atoms in the vacuum chamber (*center*). Each atom returns to its unexcited state by emitting a pair of photons. (The photon is the fundamental unit of light.) The photons travel in opposite directions through 6.5 meters of pipe, and those that pass through polarization analyzers impinge on photodetectors. Quantum mechanics predicts there should be delicate correlations in the polarizations of the oppositely directed photons; the correlation conflicts with classical theories called hidden-variables models. The experiment confirmed quantum mechanics.**



**INDEFINITENESS of a quantum system is illustrated for a photon. A sheet of polarizing film transmits all light incident on it at a right angle if the light is linearly polarized along a certain direction in the film called the transmission axis (*hatching*). This polarization state of the photon is represented by the wavy colored line at the top. The film blocks all light incident on it at a right angle if the light is linearly polarized perpendicular to the transmission axis (*wavy gray line at top*). Now suppose a photon is linearly polarized at some angle to the transmission axis between zero and 90 degrees (*bottom*). Then whether or not the photon will be transmitted is indefinite; the probability of transmission is a number between zero and 1 (the square of the cosine of the angle).**

the horizontal: either both photons will be transmitted or both will be blocked. It simply cannot happen that one photon will be transmitted and the other will be blocked. In fact, it does not matter what the orientations of the films are as long as they match each other; the outcomes of the linear-polarization experiments are strictly correlated for an infinite family of possible experiments. (Of course, no more than one of the experiments can actually be carried out.) Somehow the second photon of the pair "knows" whether to pass through its polarizing film in order to agree with the passage or nonpassage of the first photon, even though the two photons are well separated and neither has a mechanism for informing the other of its behavior. In this kind of situation, then, quantum mechanics challenges the relativistic concept of locality, which holds that an event cannot have effects that propagate faster than light (and, in particular, instantaneous effects at a distance).

It must be emphasized that all the peculiar implications that have been drawn so far—objective indefiniteness, objective chance, objective probability and nonlocality—depend crucially on the premise that a system's quantum state is a complete description of that system. A number of theorists have maintained, however, that the quantum state merely describes an ensemble of systems prepared in a uniform manner, and that this is why good predictions can be made about the statistical results of the same experiment performed on all members of the ensemble. At the same time, the argument goes, the individual members of the ensemble differ from one another in ways not mentioned by the quantum state, and this is the reason the outcomes of the individual experiments are different. The properties of individual systems that are not specified by the quantum state are known as hidden variables.

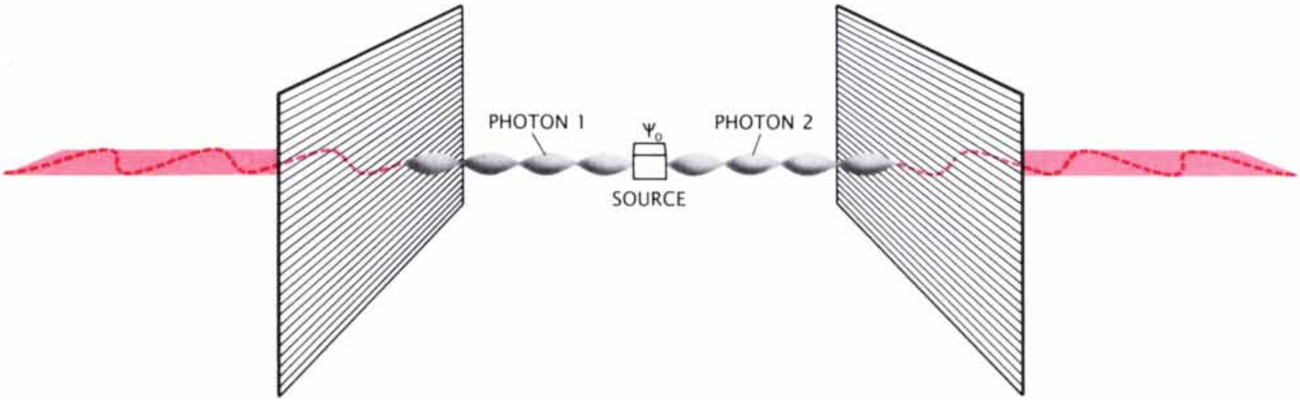
If hidden-variables theorists are correct, there is no objective indefiniteness. There is only ignorance on the part of the scientist about the values of the hidden variables that characterize an individual system of interest. Moreover, there is no objective chance and there are no objective probabilities. Most important, the quantum correlations of well-separated systems are no more surprising than the concordance of two newspapers printed by the same press and mailed to different cities.

In 1964 John S. Bell of CERN, the European laboratory for particle physics, showed that the predictions of local hidden-variables models are incompatible with the predictions of quantum mechanics. Reflection on some hidden-variables models of David Bohm of Birkbeck College London and Louis de Broglie led Bell to prove the important theorem that no model that is local (in a carefully specified sense) can agree with all the statistical predictions of quantum mechanics. In other words, there are physical situations in which the predictions of quantum mechanics disagree with those of every local hidden-variables model [see "The Quantum Theory and Reality," by Bernard d'Espagnat; SCIENTIFIC AMERICAN, November, 1979].

The idea of Bell's theorem can be grasped, at least in part, by returning to consider the quantum state $\Psi_0$. As noted above, the results of linear-polarization experiments performed on a pair of photons in this state must be strictly correlated when the angle between the transmission axes of the two polarizing films is zero degrees (as it is when both axes are aligned vertically). It should not be surprising to learn, therefore, that for the state $\Psi_0$ there is always at least a partial correlation between the outcomes, no matter what the angle between the transmission axes is. (Specifically, if one of the photons is transmitted through its polarizing film, then the probability that the other photon will be transmitted through its film is the square of the cosine of the angle between the two transmission axes.)

Consequently a hidden-variables model that agrees with all the statistical predictions of quantum mechanics must assign quantities to each pair of photons in the ensemble in a delicate way in order to guarantee the strict or partial correlations at every angle between the axes. But the condition of locality requires that the quantities assigned to each photon in a pair must be independent of the orientation of the polarizing film on which the other photon impinges and independent of the other photon's passage or nonpassage. It is this locality condition that makes quite impossible the delicate adjustments that would be necessary for reproducing all the correlations, strict and partial, implied by $\Psi_0$.

Bell's theorem shows that in principle one can determine experimentally which is correct: quantum mechanics or the local hidden-variables models. It was important to do such a test because, in spite of the immense body of confirming evidence




**CORRELATIONS** between the polarizations of two photons occur when the photons are in a special state called $\Psi_0$ (after the letter psi in the Greek alphabet). The state can be formed by superposing the state in which both photons are linearly polarized along a vertical axis with the state in which they are both linearly polarized along a horizontal axis. The state $\Psi_0$ contains equal amounts of the vertically polarized state and the horizontally polarized state. Now imagine that polarizing films with horizontally oriented transmission axes are inserted in the paths of the photons. Since $\Psi_0$ contains equal amounts of the two states, there is a 50 percent probability that both photons will be transmitted through their respective films and a 50 percent probability that both will be blocked. What cannot happen is that one photon will be transmitted and the other will be blocked: the outcomes of the linear-polarization experiments are strictly correlated. In fact, it does not matter what the orientations of the films are as long as they match each other; somehow the second photon of the pair "knows" whether to pass through its polarizing film in order to agree with the passage or nonpassage of the first photon, even though the photons are well separated.

for quantum mechanics at the time Bell proved his theorem, the very points where quantum mechanics is without equivocation irreconcilable with common sense had not yet been probed.

In 1969 John F. Clauser, then at Columbia University, Michael A. Horne of Boston University, Richard A. Holt, then at Harvard University, and I proposed a design for the requisite test. Pairs of photons with correlated linear polarizations were to be obtained by exciting atoms to an appropriate initial state; the atoms would subsequently return to the unexcited state by emitting two photons. Filters and lenses would ensure that when the photons flew off in opposite or virtually opposite directions, one photon would impinge on a polarization analyzer and the other would impinge on another analyzer. By switching between two orientations of each analyzer and recording the number of photon pairs transmitted in each of the four possible combinations of orientations of the two analyzers, measurements of correlations of transmissions of the photons of a pair could be made.

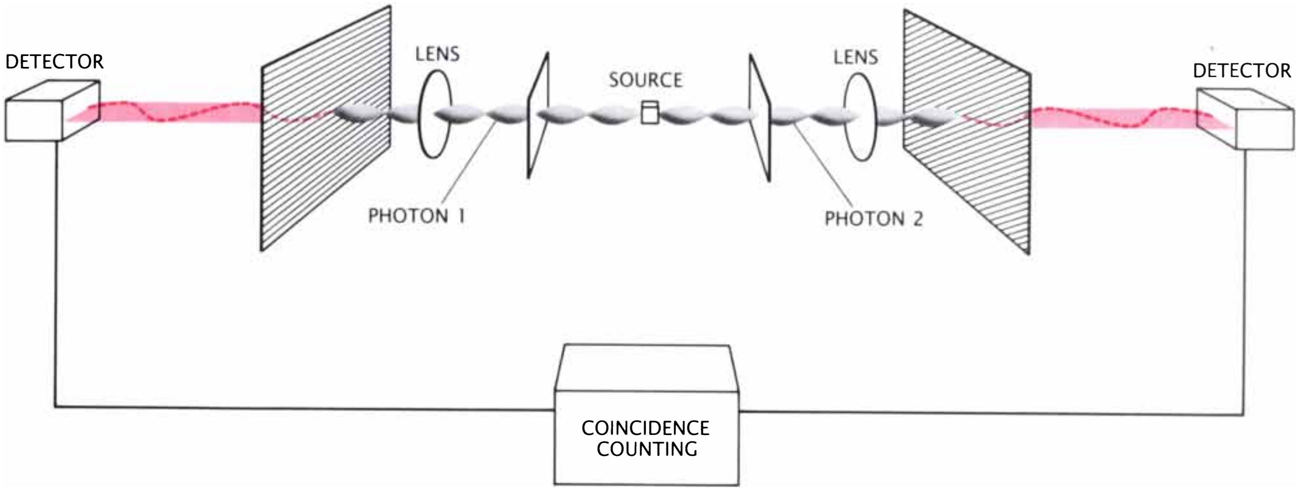
We suggested that either calcite crystals or piles of glass plates serve as the polarization analyzers, since each of them is much more efficient than an actual polarizing film in blocking photons polarized perpendicular to the transmission axis. Photodetectors placed behind the analyzers would detect a fixed fraction of the photons passing through the analyzers. If two photons, one at each detector, were registered within 20 nanoseconds (billionths of a second) of each other, the probability would be quite high that they were emitted by the same atom. Since the lenses would collect the two photons over a finite angle, the quantum state would not be exactly the $\Psi_0$ state discussed above but a modified state $\Psi_1$, which also leads to correlations that cannot be reproduced by any local hidden-variables model.

The experiment was done by Stuart J. Freedman and Clauser at the University of California at Berkeley in 1972, by Edward S. Fry and Randall C. Thompson at Texas A. & M. University in 1975 and by other groups after that. Most of the experimental results agree with the correlation predictions of quantum mechanics and disagree with the hidden-variables models. Moreover, the reliability of the dissenting experiments is suspect because of subtle weaknesses in their design.

Yet until very recently all the experiments had a loophole that allowed staunch defenders of hidden-variables models to maintain their hopes: the polarization analyzers were kept in their respective orientations for intervals of a minute or so, which is ample time for the exchange of information between the analyzers by some hypothetical mechanism. As a result the defenders could contend that the special theory of relativity does not imply the validity of Bell's locality condition in the physical situation of the experiments. But then these experiments would not serve as decisive tests between quantum mechanics and the local hidden-variables models.

To block this loophole, Alain Aspect, Jean Dalibard and Gérard Roger of the Institute of Optics of the University of Paris did a spectacular experiment in which the choice between the orientations of the polarization analyzers is made by optical switches while the photons are in flight. In their experiment, which required eight years of work and was completed only in 1982, each switch is a small vial of water in which standing waves are periodically generated ultrasonically. The waves serve as diffraction gratings that can deflect an incident photon with high efficiency. If the standing waves are turned on, the photon will be deflected to an analyzer that is oriented one way; if the standing waves are turned off, the photon will travel straight to an analyzer that is oriented another way.

The switching between the orientations takes about 10 nanoseconds. The generators that power the two switches operate independently, although (unfortunately for the complete definitiveness of the experiment) the operation is periodic rather than random. The distance between the analyzers is 13 meters, so that a signal moving at the speed of light (the highest speed allowed by the special theory of relativity) takes 40 nanoseconds to travel between them. Consequently the choice of orientation for the first polarization




**SEARCH FOR CORRELATIONS** between members of pairs of photons was carried out in the 1970's by a number of investigators. The photon pairs were emitted in energy-state transitions of calcium and mercury atoms; each photon impinged on a polarization analyzer. Quantum mechanics predicts there must be delicate correlations in the passage or nonpassage of the photons through their analyzers, even though the photons have no apparent means of communicating with each other. The experiments mainly confirmed quantum mechanics, but they had a loophole: the orientations of the two analyzers were fixed before the photons were emitted. Consequently it was possible that information was somehow exchanged between the analyzers.

analyzer ought not to influence the transmission of the second photon through the second analyzer, and the choice of orientation for the second analyzer ought not to influence the transmission of the first photon through the first analyzer. The experimental arrangement is thus expected to satisfy Bell's locality condition. It follows that—according to Bell's theorem—there should be some violations of the quantum-mechanical predictions of correlations in the experimental outcome.

In point of fact, however, the experiment yielded just the opposite result. The correlation data agree within experimental error with the quantum-mechanical predictions that are calculated on the basis of the quantum state $\Psi_1$. Moreover, the data disagree by more than five standard deviations with the extreme limits allowed, according to Bell's theorem, by any of the local hidden-variables models.

Even though the experiment of Aspect and his colleagues is not completely definitive, most people believe the prospects of overthrowing the results by future experiments are extremely small. It seems unlikely that the family of local hidden-variables models can be salvaged. The strange properties of the quantum world—objective indefiniteness, objective chance, objective probability and nonlocality—would appear to be permanently entrenched in physical theory.

One of the strangest properties of the quantum world is nonlocality. Can the fact that under some circumstances a measurement on one photon apparently instantaneously affects the result of a measurement on another photon be capitalized on to send a message faster than the speed of light? Fortunately for the special theory of relativity the answer to the question is no. An underlying assumption of that theory—that no signal can travel faster than light—is preserved.

Here is a brief argument that shows why. Suppose two people want to communicate by means of a device similar to the one for testing local hidden-variables models. Between the observers a source emits pairs of correlated photons. Each observer is provided with a polarization analyzer and a photodetector. The observers are free to orient the transmission axes of their analyzers any way they choose.

Suppose the observers agree to align the transmission axes vertically. Then every time a pair of photons is emitted there will be a strict correlation in the outcome: either both photons will pass through the analyzers or both will be blocked. But the strict correlation is of no value for each observer in isolation from the other. The first observer will note that half of the time photons pass through the first analyzer, on the average, and half of the time they are blocked. The second observer will note the same thing for the second analyzer. In other words, each observer in isolation sees only a random pattern of transmissions and blockages.

Now imagine that the first observer tries to encode some information and send it to the second observer by changing the orientation of the first polarization analyzer. Depending on the orientation of that analyzer, there will be either a strict or a partial correlation between the outcomes of the events at each detector. Once again, however, each observer will note that on the average half of the time photons pass through the analyzer and half of the time they are blocked. In general, no matter what the orientations of the analyzers are, each observer in isolation sees only a random (and statistically identical) pattern of transmissions and blockages. The quantum correlations between the photons can be checked only by comparing the data accumulated at the two detectors. Hence the attempt to exploit the quantum correlations to send messages faster than light cannot succeed.

In this sense there is a peaceful coexistence between quantum mechanics and relativity theory, in spite of quantum-mechanical nonlocality. For this reason it would be misleading (and wrong) to say that nonlocality in the quantum-mechanical sense is a reversion to action at a distance, as in the prerelativistic gravitational theory of Newton. It is tempting to characterize quantum-mechanical nonlocality as "passion at a distance," not with any pretension to provide an explanation for the strange correlations, but only to emphasize that the correlations cannot be exploited to exert a controlled influence more rapidly than a light signal can be sent.

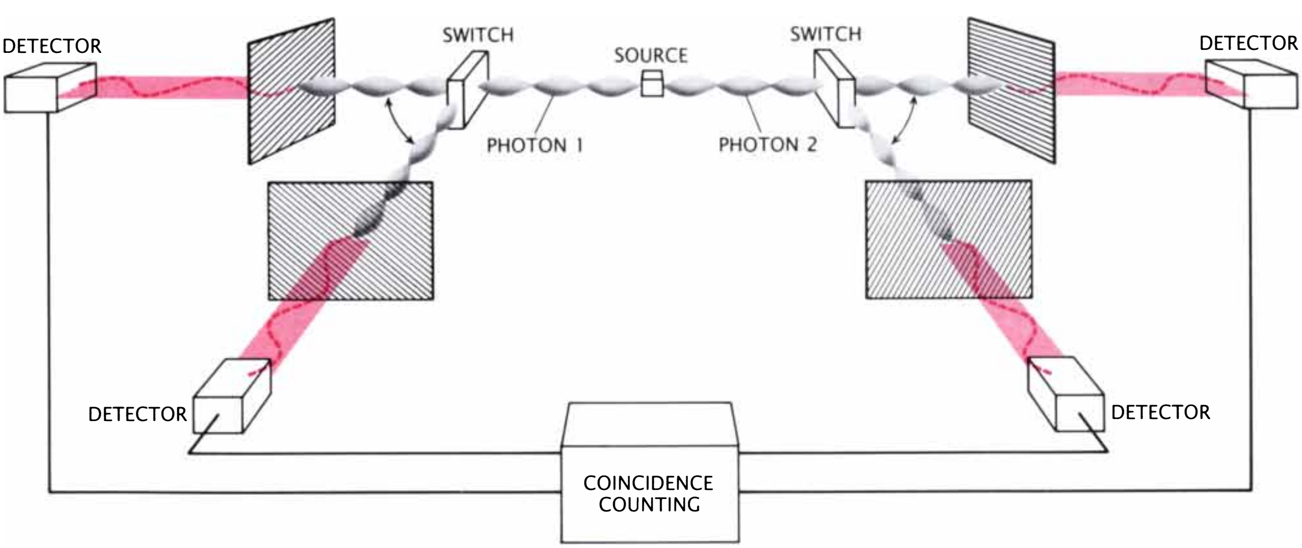
Another test, called the delayed-choice experiment, which was proposed in 1978 by John Archibald Wheeler, then at Princeton University, also reveals the strangeness of the quantum world. The basic apparatus of the experiment is an interferometer, in which a light beam can be split and recombined. A pulse of light from a laser is fired at the beam splitter, which is oriented in such a way that half of the light passes through the splitter and half is reflected at right angles to the direction of the incident pulse. If the light from the two paths is subsequently recombined, an interference pattern can be detected, which demonstrates the wavelike quality of light.

Now suppose the pulse of laser light is attenuated so severely that at any time there is only one photon in the interferometer. In this case two different questions can be asked about the photon. Does the photon take a definite route so that it is either transmitted or reflected by the beam splitter, thereby exhibiting a particlelike property? Or is the photon in some sense simultaneously transmitted and reflected so that it interferes with itself, thereby showing a wavelike property?

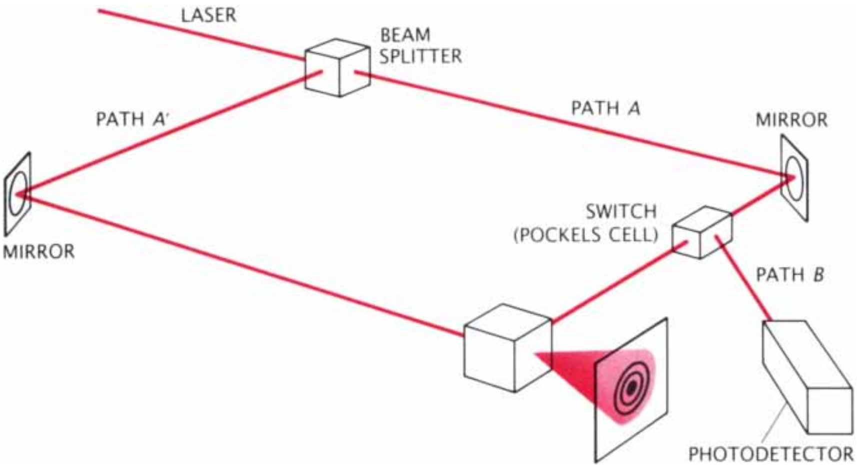
An answer was recently supplied by Carroll O. Alley, Oleg G. Jakubowicz and William C. Wickes of the University of Maryland at College Park and independently by T. Hellmuth, H. Walther and Arthur G. Zajonc of the University of Munich. Both groups found that a photon behaves like a particle when particlelike properties are measured and that it behaves like a wave when wavelike properties are measured. The remarkable novelty of the results is that the experiment was arranged so that the decision to measure particlelike or wavelike properties was made after each photon had interacted with the beam splitter. Consequently the photon could not have been "informed" at the crucial moment of interaction with the beam splitter whether to behave like a particle and take a definite route or to behave like a wave and propagate along two routes.

The length of both routes in the interferometer was about 4.3 meters, which a photon can traverse in roughly 14.5 nanoseconds. Obviously this does not allow enough time for an ordinary mechanical device to switch between measuring particle- and wavelike properties. The feat was made possible with a switch called a Pockels cell, which can be actuated in nine nanoseconds or less. A Pockels cell contains a crystal that becomes birefringent when a voltage is applied across it: light polarized along one axis of the crystal propagates at a velocity different from that of light polarized along the perpendicular direction. Given the proper choice of voltage and configurational geometry, light polarized in one direction when it enters the cell will emerge polarized in the perpendicular direction. The Pockels cell was inserted in one of the two routes the photon could take after interacting with the beam splitter [*see illustration on next page*].

A piece of polarizing film was the other essential element needed to switch between measurements of particlelike and wavelike properties. Light emerging from the Pockels cell impinged on the film. If the cell was "on," the polarization of the light was such that the polarizing film reflected the light into a photodetector, thereby answering the question of which route and confirming the photon's particlelike properties. If the cell was "off," the polarization of the light was such that the polarizing film transmitted the light, which then was combined with the contribution coming from the other route; interference ef-




**RAPID SWITCHING between orientations of polarization analyzers as photons flew was the hallmark of the experiment done by Aspect and his colleagues (*see illustration on page 47*), which was completed in 1982. When a switch was "on," a photon was deflected to an analyzer that was oriented one way; when the switch was "off," the photon traveled straight to an analyzer that was oriented another way. The time required for light to travel between the analyzers was greater than the time required to switch between orientations, so that the choice of orientation for each analyzer could not influence the observation made at the other analyzer. (Unfortunately for complete definitiveness, however, the switching was periodic rather than random.) The experiment confirmed quantum mechanics; it would appear that the strange implications of the theory must be accepted.**




**DELAYED-CHOICE EXPERIMENT is another test that reveals the strangeness of the quantum world. A photon impinges on a beam splitter. Two questions about the photon can be asked. Does the photon take a definite route so that it is either transmitted or reflected by the beam splitter, thereby exhibiting a particlelike property? Or is the photon in some sense both transmitted and reflected so that it interferes with itself, exhibiting a wavelike property? To find out, a switch is positioned in one of the two paths the photon can take after interacting with the beam splitter (*here, path* A). If the switch is on, the light is deflected into a photodetector (*path* B), thereby answering the question of which route and confirming the photon's particlelike properties. If the switch is off, the photon is free to interfere with itself (*paths* A *and* A') and produce an interference pattern, demonstrating the photon's wavelike properties. Results from the experiment show that a photon behaves like a wave when wavelike properties are measured and behaves like a particle when particlelike properties are measured. Remarkably, the switch was triggered after the photon had interacted with the beam splitter, so that the photon could not have been "informed" whether to behave like a particle and take a definite route or to behave like a wave and propagate simultaneously along two routes.**

fects confirmed the photon's wavelike aspect.

Both groups of investigators have reported results that are in excellent agreement with quantum mechanics. Their work shows that the choice between the two questions can be made after an individual photon has interacted with the beam splitter of an interferometer.

How are the results of the delayed-choice experiment to be interpreted? It is worthwhile first to disclaim one extravagant interpretation that has sometimes been advanced: that quantum mechanics allows a kind of "reaching into the past." Quantum mechanics does not cause something to happen that had not happened previously. Specifically, in the delayed-choice experiment quantum mechanics does not cause the photon to take a definite route at time zero if 12 nanoseconds later the Pockels-cell switch is turned on, and it does not cause the photon to take both routes, in wavelike fashion, if the switch is off.

A more natural interpretation is that the objective state of the photon in the interferometer leaves many properties indefinite. If the quantum state gives a complete account of the photon, then that conclusion is not surprising, since in every quantum state there are properties that are indefinite. But the conclusion does raise a further question: How and when does an indefinite property become definite? Wheeler's answer is that "no elementary quantum phenomenon is a phenomenon until it is a registered phenomenon." In other words, the transition from indefiniteness to definiteness is not complete until an "irreversible act of amplification" occurs, such as the blackening of a grain of photographic emulsion. Students of the foundations of quantum mechanics disagree about the adequacy of Wheeler's answer, however. The next experiment shows why the question is still open.

In 1935 Erwin Schrödinger proposed a famous thought experiment. A photon impinges on a half-silvered mirror. The photon has a probability of one-half of passing through the mirror and a probability of one-half of being reflected. If the photon passes through the mirror, it is detected, and the detection actuates a device that breaks a bottle of cyanide, which in turn kills a cat in a box. It cannot be determined whether the cat is dead or alive until the box is opened.

There would be nothing paradoxical in this state of affairs if the passage of the photon through the mirror were objectively definite but merely unknown prior to observation. The passage of the photon is, however, objectively indefinite. Hence the breaking of the bottle is objectively indefinite, and so is the aliveness of the cat. In other words, the cat is suspended between life and death until it is observed. The conclusion is paradoxical, but at least it concerns only the results of a thought experiment.

It is now more difficult to dismiss the paradoxical nature of the conclusion, because something similar to Schrödinger's thought experiment has recently been achieved by a number of groups of investigators including Richard F. Voss and Richard A. Webb of the IBM Thomas J. Watson Research Center in Yorktown Heights, Lawrence D. Jackel of the AT&T Bell Laboratories, Michael H. Devoret of Berkeley and Daniel B. Schwartz of the State University of New York at Stony Brook. Their work has relied to a certain extent on calculations that were done by Anthony J. Leggett of the University of Illinois at Urbana-Champaign and Sudip Chakravarty at Stony Brook, among other investigators.

The experimental apparatus consists of an almost closed superconducting ring. A thin slice of insulating material (called a Josephson junction) interrupts the ring, but an electric current can circulate around the ring by "tunneling" through the insulator. The current generates a magnetic field.

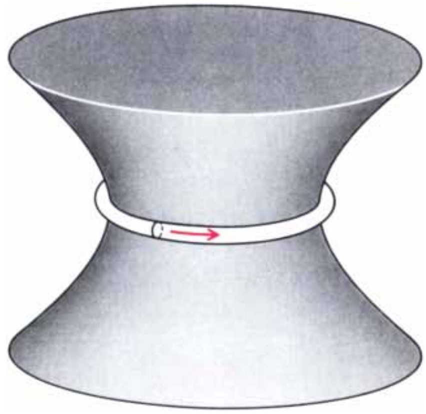
The quantity that is of interest in the system is the magnetic flux through the ring, which (when the field is uniform) is equal to the area of the ring multiplied by the component of the magnetic field perpendicular to the plane of the ring. If the ring were uninterrupted, the flux would be trapped within the ring, but the insulator allows the flux to slip from one value to another. With modern magnetometers the flux can be measured with fantastic accuracy. The fact that the flux arises from the motion of enormous numbers of electrons (on the order of $10^{23}$) in the superconducting ring justifies speaking of the flux as a macroscopic quantity. There is now good evidence that states of the superconducting ring can be prepared in which the flux does not have a definite value—a quantum-mechanical feature that had previously been established only for observables of microscopic systems.

To understand how this indefiniteness is demonstrated experimentally, it is necessary to know that for each value of the flux the ring has a certain potential energy. Ordinarily one would not expect that the flux through the ring could change spontaneously from one value to another, because a potential-energy barrier separates adjacent values of the flux from each other. Classical physics forbids the transition between two such values of the flux unless some external source of energy, typically thermal, is supplied to traverse the barrier between them. In quantum mechanics, on the other hand, the barrier can be tunneled through without any external source of energy. The groups of investigators mentioned above have shown that the flux does change between two values, and that the change cannot be entirely accounted for thermally; the observed tunneling must be at least partially quantum mechanical, particularly at very low temperatures. But quantum-mechanical tunneling rests essentially on the indefiniteness of the flux, which thus cannot be localized definitely at or close to one value or another.

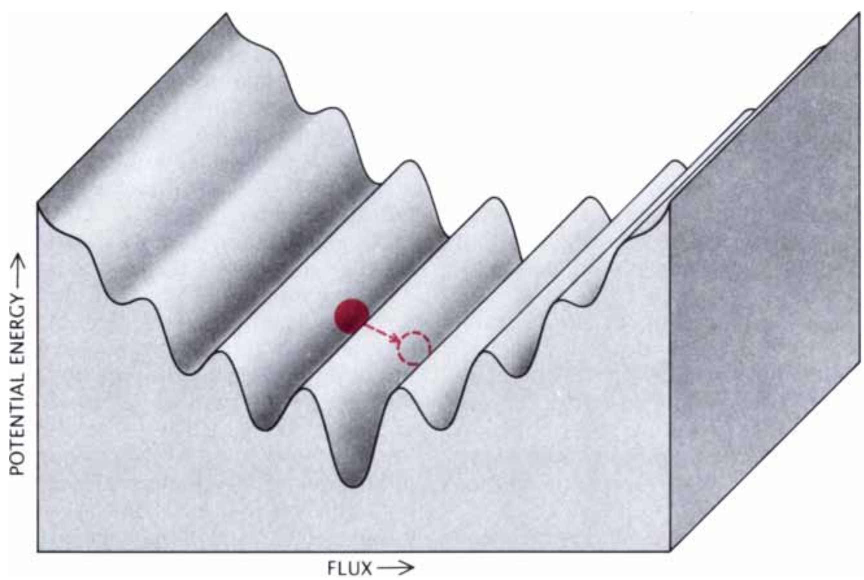
The experimental demonstration of quantum indefiniteness in a macroscopic variable does not ipso facto contradict the statement by Wheeler quoted above, but it does show that amplification from a microscopic to a macroscopic level does not in itself exorcise quantum-mechanical indefiniteness. The emphasis in Wheeler's statement about an "irreversible act of amplification" must be placed on the word "irreversible." The conditions for the occurrence of an irreversible process are far from settled in contemporary theoretical physics. Some students of the subject (including me) believe new physical principles must be discovered before we can understand the peculiar kind of irreversibility that occurs when an indefinite observable becomes definite in the course of a measurement.

The strangeness of the quantum world continues to be explored. Still other experiments have recently been performed or are now under way; two classes of these experiments should be mentioned here, even though there is no room to discuss them in detail. In the neutron-interferometer experiments of Helmut Rauch and Anton Zeilinger of the Atomic Institute of the Austrian Universities, Samuel A. Werner of the University of Missouri at Columbia and Clifford G. Shull of the Massachusetts Institute of Technology and their associates, the wave function of a neutron is split by a sheet of crystal and recombined by one or two other sheets. The interference effects exhibited in the recombination demonstrate a number of remarkable properties, including the indefiniteness of the neutron's route through the interferometer.

Finally, R. G. Chambers of the University of Bristol, G. Möllenstedt of the University of Tübingen and Akira Tonomura of Hitachi, Ltd., have confirmed by electron interferometry the remarkable Aharonov-Bohm effect, in which an electron "feels" the presence of a magnetic field that is in a region where there is zero probability of finding the electron. This is a striking demonstration of a kind of nonlocality different from, although remotely related to, the nonlocality exhibited by correlated photon pairs. A thorough understanding of the relation between the two kinds of nonlocality as well as the many other perplexing issues raised by experiments probing the nature of the quantum world awaits further work.



**MACROSCOPIC SYSTEM** can under some circumstances exist in a state in which a macroscopic variable has an indefinite value; indefiniteness is not limited to microscopic systems, such as the photon. The system shown here is a superconducting ring that does not quite bend back on itself. A thin slice of insulating material separates the two ends of the ring from each other, and an electric current is made to circulate around the ring by "tunneling" through the insulator. The current generates a magnetic field. If the ring were continuous, the magnetic flux through the ring (the area of the ring multiplied by the component of the magnetic field perpendicular to the plane of the ring) would be trapped at a fixed value, but the insulator allows the flux to slip from one value to another. Surprisingly, the flux does not have a definite value.




**INDEFINITENESS** in the system shown at the top of the page is depicted schematically. Each value of the flux through the superconducting ring has a certain potential energy associated with it. Ordinarily one would not expect that the flux through the ring could spontaneously change from one value to another, because a potential-energy barrier separates the adjacent values of the flux from each other. The barriers can be thought of as hills, and the state the system is in can be represented as a ball residing in a valley among the hills. According to classical physics, a transition between two values separated by a barrier requires outside energy (to push the ball over the hill). Quantum mechanically, however, the barrier can be tunneled through without any external source of energy. Tunneling is essentially a manifestation of the indefiniteness of the flux.