Loophole Closed in Quantum Mechanics Test

The violations of Bell's inequality predicted by quantum mechanics can no longer be attributed to communication between the parts of the experimental apparatus

The first results from a long awaited experiment to test the completeness of quantum mechanics are now in. The experiment by Alain Aspect, Jean Dalibard, and Gérard Roger of the Institute of Theoretical and Applied Optics at the University of Paris–South in Orsay for all practical purposes closes one of the loopholes left open in several previous investigations of a similar type.* Only one more loophole remains for physicists who want to escape having to wrestle with the philosophical implications of quantum mechanics (*Science*, 30 July 1982, p. 435).

No one seriously doubts that quantum mechanics is a valuable tool for describing the behavior of physical systems at the atomic level. It is just that quantum mechanics seems to reject our intuitive notion of realism—that is, that physical systems have well-defined properties whether any one measures them or not.

Consider the following experiment, which is similar to the one Aspect and his co-workers carried out. A calcium-40 atom excited by the absorption of laser light into an electronic state with total angular momentum equal to zero decays to its ground state, also with zero total angular momentum, by the emission of two photons. The decay is through an intermediate state with angular momentum quantum number $J = 1$. Conservation of linear and angular momentum requires that those photons that fly off in opposite directions be circularly polarized in the same sense (both right or both left).

Quantum mechanics views the wave function of a circularly polarized photon as an equal mixture or linear superposition of (say) horizontally and vertically linearly polarized wave functions. Thus, if one were to place a linear polarization analyzer in front of a circularly polarized photon, there is a 50-50 chance that it will pass, whatever the orientation of the analyzer.

So far, so good. Now, place linear polarization analyzers in front of each of the photons from an excited calcium atom. From what has been said so far, one would expect no correlation between the linear polarizations of the photons, since each one has a 50-50 chance of being linearly polarized in either direction. Yet, the correlation is 100 percent. The photon pairs either both pass or neither passes if the orientations of the analyzers are the same, and only one passes if the orientations are perpendicular.

From the quantum mechanical point of view, the key to this "paradox" is the fact that at no time did anyone actually measure the circular polarization states of the photons, so one cannot assert that there were two circularly polarized photons whose wave functions consisted of equal parts horizontally and vertically polarized components. In quantum mechanics, one cannot say a physical system has a particular property until it is measured. In fact, if one had measured the circular polarizations before the linear polarizations, the correlation between the latter would have been random. This is a particular example of the more general phenomenon of interference. In quantum mechanics, when there are two possible ways for something to occur, the total probability is the square of the sum of the wave functions for each path. However, when each path is examined specifically, the total probability is the sum of the squares—that is, the interference disappears.

> "The new results should not be interpreted as suggesting . . . faster than light communication."

Nonetheless, physicists as renowned as Albert Einstein have been troubled by the inability of quantum mechanics to state with certainty what the properties of a physical system are at every moment. In 1935, Einstein, together with Boris Podolsky and Nathan Rosen, published a paper† analyzing an experiment somewhat different from that involving the linear polarization of photons, but one that ran into a similar conceptual problem. One solution proposed later was the existence of "hidden variables" or supplementary parameters that were inaccessible to measurement but which, if known, would allow one to predict the outcome of any measurement.

From an operational point of view, the existence of hidden variables seemed to be of little value, since they could not affect the outcome of any experiment. However, in 1965, John Bell of the European Laboratory for Particle Physics (CERN) published a mathematical proof that under certain circumstances hidden variables and quantum mechanics were incompatible and were experimentally distinguishable. Hidden variables are a specific instance of the more general proposition of realism. An additional restriction not discussed so far is the assertion of special relativity that energy cannot travel faster than the speed of light, a property termed locality. Bell's proof applied to realistic, local theories.

The original proof did not apply to systems such as the two-photon emitting, excited calcium-40 atom. But several theorists, including Bell, have generalized the proof to cover additional situations, such as calcium-40. Interestingly, the proofs show that there is *no* contradiction between realistic, local theories and quantum mechanics for the experiment already described. Hidden variables could, for example, explain the 100 percent correlation between the linear polarizations of the two photons, when the polarization analyzers are parallel, and the zero percent, when they are perpendicular. It is when the analyzers are at arbitrary angles to one another that quantum mechanics predicts slightly higher correlations between the polarizations than do realistic, local theories.

The formal expression of the different predictions of quantum mechanics and realistic, local theories is in the form of an inequality (constructed from the correlations between the linear polarizations at four relative orientations of analyzers) that must be obeyed by all realis-

*A. Aspect, J. Dalibard, G. Roger, *Phys. Rev. Lett.* **49**, 1804 (1982).

†A. Einstein, B. Podolsky, N. Rosen, *Phys. Rev.* **47**, 777 (1935).

0036-8075/83/0107-0040$01.00/0

tic, local theories. The inequality tested by the French investigators was derived in 1969 by John Clauser, now at the Lawrence Livermore National Laboratory, Michael Horne and Abner Shimony of Boston University, and Richard Holt, now at the University of Western Ontario. Their inequality stated that a certain sum S must lie between -1 and 0. The maximum value of S allowed by quantum mechanics occurs when the polarization analyzers have orientations such that the angle between them is 22.5 or 67.5 degrees. The theoretical quantum mechanical value for S is then 0.112. The value observed by Aspect and his colleagues is 0.101 ± 0.020. This is five standard deviations away from the limit imposed by realistic, local theories. In another experiment, the investigators also reproduced the cosine angular dependence predicted by quantum mechanics between the correlations for six orientations between 0 and 90 degrees.

In the last 10 years, several groups have carried out experiments of this type involving polarization correlation measurements of light emitted from excited calcium or mercury atoms and from electron-positron (positronium) annihilation and spin angular momentum correlation of pairs of protons prepared in a certain way. The overwhelming evidence is in favor of quantum mechanics. What the recent French results contribute is the closing of a loophole that previous experiments could not eliminate. The loophole is the possibility of some kind of signal being transmitted from one part of the experiment to another that allows photons to "know" what polarization they are supposed to have and thereby guarantees the observed correlations. The first photon arriving at an analyzer could, for example, send a message back to the source of calcium atoms telling it what polarization orientation was being checked for. All subsequent pairs of emitted photons would then know what state they should be in. This communication is possible in principle because the settings of the polarization analyzers are not changed for each pair of arriving photons. Such signals would not have to travel faster than the speed of light, and so would not violate the requirements of realistic, local theories.

What the French physicists did was to devise rapidly switching polarization analyzers. It takes a photon about 20 nanoseconds to travel from the calcium atom to the detector in their experiment, but the polarization analyzer is switched every 10 nanoseconds. Thus, there is no time for any signal to be transmitted between the parts of the apparatus and influence the outcome of any measurement. The means by which switching was achieved was the generation of standing ultrasonic waves in water with the use of two lithium niobate piezoelectric crystals. At certain times during each wave cycle, incoming light would be either transmitted or diffracted, the two beams going to polarization analyzers of different orientations. The frequencies of the exciting electrical signals to the two pairs of crystals, one pair for each photon beam, differed so that the wave patterns in the two water switches had different time dependences. Thus, the orientations of the polarizers seen by each photon would change independently, if not perfectly randomly. Shimony told *Science* that the lack of true randomness means that "Their experiment is not ideal for their purpose, but nevertheless quite close to ideal. It is a wonderful achievement."

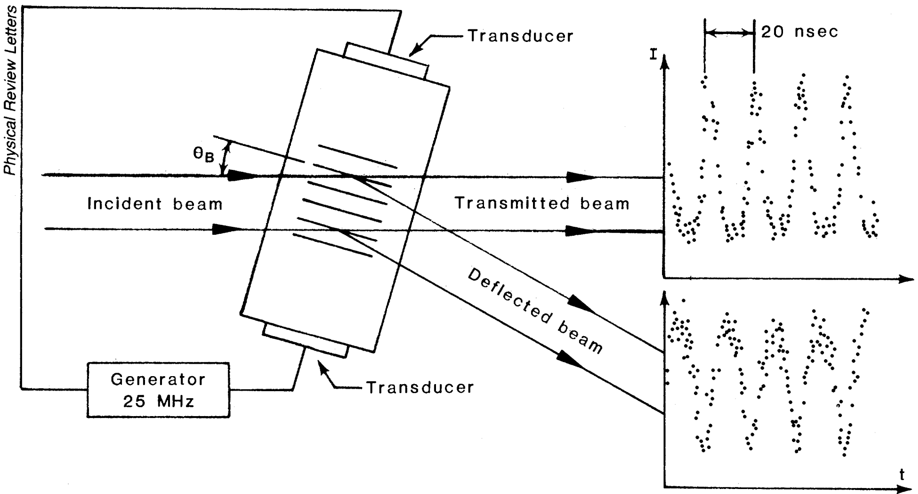
The remaining loophole, not touched by any experiment so far, has to do with the efficiency of the devices that detect the photons or other particles in correlation experiments. Because the detector systems are relatively inefficient, only a small fraction of the emitted particles are registered. It is therefore possible to argue that for some reason the particles that are detected are in some way different from those that are not. Thus, the detected particles are not representative of all the particles, and the observed correlations need not apply to the undetected particles. No experiments to deal with this objection are or are about to be under way, however.

Assuming that such an experiment will be carried out some day and that it will support quantum mechanics, what can one say? One possibility is that there are mysterious signals between parts of the apparatus of the aforesaid type but that they travel faster than the speed of light—that is, locality would be violated. There are perhaps a few scientists who would welcome the existence of such signals as a possible explanation for paranormal phenomena, such as ESP. But among most physicists, the focus is on the concerns originally raised by Einstein, who was not the least worried that the speed of light might be exceeded. In fact, several physicists contacted by *Science* emphasized that the new results should not be interpreted as suggesting the possibility of faster than light communication. And Aspect says, "I don't find any connection between this problem and paranormal phenomena." In this case, it is one's notion of realism that may have to change. For example, Francis Pipkin of Harvard, who carried out a 1973 test of Bell's inequality with Holt, says that now "It is even harder to create a local, hidden variables theory in which photons carry information that allow things to come out right."

Perhaps the most sensible outlook for the moment is still that of California Institute of Technology physicist Richard Feynman, who wrote some years ago:‡

"Do you still think there is a 'paradox'? Make sure that it is, in fact, a paradox about the behavior of Nature by setting up an imaginary experiment for which the theory of quantum mechanics would predict inconsistent results via two different arguments. Otherwise the 'paradox' is only a conflict between reality and your feeling of what reality 'ought to be.'

"Do you think that is *not* a 'paradox,' but that it is still very peculiar? On that we can all agree."—**ARTHUR L. ROBINSON**



Physical Review Letters

Fast optical switch

A light beam passing through the switch changes direction every 10 nanoseconds.

‡R. P. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, New York, 1965), vol. 3, pp. 18–19.