considered a strong candidate to be a control sequence. It did not appear to be in this study, however.

McKnight and Kingsbury note that the guanine-rich and cytosine-rich segments contain a six-base pair inverted repeat that could permit the two regions to pair with one another, to form an intrastrand stem-loop structure. They propose that the formation of this structure may somehow facilitate attachment of RNA polymerase II (the transcribing enzyme) onto the *tk* gene control region. This contact would then allow transcription to begin at a specific base.

As yet they do not have direct evidence that the intrastrand looping out occurs and is necessary for transcription initiation, but this should now be easy to test by introducing point mutations that destroy the intrastrand base pairing capacity. If these changes do reduce transcription efficiency, the investigators can try to remedy the situation by introducing, into one gene, complementing mutations that restore the base-pairing.

—JEAN L. MARX

# Quantum Mechanics Passes Another Test

## *French photon polarization correlation experiment finds strongest violation yet of Bell's inequality*

The success of quantum theory in describing physical phenomena at the molecular level and below is unquestioned. But since 1965 it has been known that quantum mechanics makes certain predictions that are contrary to what is allowed by any member of the class of realistic, local theories. Realism, which to the modern mind might be called common sense, argues that there is an objective reality that exists independent of whether someone observes it or not. Locality stems from the special theory of relativity and its premise that forces or information can only travel between bodies at velocities less than or equal to that of light.

In short, quantum mechanics, special relativity, and realism cannot all be true. Several experiments over the last 10 years strongly support the predictions of quantum mechanics but do not test whether it is special relativity or realism that has to go.

The latest experiment is by Alain Aspect, Philippe Grangier, and Gérard Roger of the Institute of Theoretical and Applied Optics of the University of Paris-South in Orsay (*1*). The investigators measured correlations between the linear polarizations of the two photons emitted when a calcium-40 atom, initially in an excited state with a total angular momentum $J = 0$ decays to its ground state, also with total angular momentum $J = 0$. The decay is by way of an intermediate state with total angular momentum $J = 1$. And the two photons move away from the calcium atom in opposite directions.

What would one expect to see? From the quantum theory as applied to atoms, it is required that the linear polarizations of the photons be parallel. Thus, if polarization analyzers are placed in front of photodetectors (assumed to be 100 percent efficient) and are aligned parallel, either both detectors will register a photon or neither will. If the analyzers are perpendicular, only one of the detectors will register a photon. So far, no problem. The predictions of quantum mechanics and realistic, local theories diverge only when the polarization analyzers assume arbitrary relative orientations.

In 1965, John Bell of the European Laboratory for Particle Physics (CERN) near Geneva published his findings for the case of particles with spin angular momentum of ½. Bell showed that every realistic, local theory of two spin-½ particles obeys a certain inequality that quantum mechanics violates. Subsequently, Bell and several other theorists independently rederived similar inequalities that were appropriate for particular sets of circumstances (*2*).

The inequality tested by the French researchers was found in 1969 by John Clauser, then at Columbia University, Michael Horne and Abner Shimony of Boston University, and Richard Holt, then at Harvard University. The inequality applies to the linear polarization of photons (spin-1 particles) in the situation where an analyzer would pass a photon of polarization either parallel or perpendicular and tell the observer which it was. At any arbitrary relative orientation of the analyzers, four outcomes are possible: both photons are polarized parallel, both are perpendicular, one is parallel and the other is perpendicular, and vice versa. The theorists proved that measurements of a large number of outcomes at each of four relative orientations would have to be such that a certain sum satisfied an inequality. The inequality states that the magnitude of a sum $S$ is less than or equal to 2. A quantum mechanical calculation of the same sum gives the result $S$ less than or equal to $2\sqrt{2}$.

In general, because of photodetectors that are not 100 percent efficient, polarization analyzers that do not perfectly pass or block polarized light, the finite size of optical elements, diverging light beams, and so on, the quantum mechanical sum $S$ can never be achieved. For the French experiment, the quantum mechanical $S$ calculated with these limitations taken into account was $2.70 \pm 0.05$. The measured value was $2.697 \pm 0.015$, a rather impressive violation of Bell's inequality. Moreover, according to quantum mechanics, a correlation coefficient $E$ (defined as the sum of the outcomes in which both photons are parallel or perpendicular minus the outcomes in which one photon is parallel and the other perpendicular) has a cosine dependence on the angle between the analyzers. Aspect and his colleagues reproduced this dependence to within 1 percent in measurements at six different orientations.

The sum $S$ is obtained from these correlation coefficients taken at four angles. Broadly speaking, correlation answers the question: How much can one tell about the polarization of one photon from a measurement on the other photon? When the orientations of the polarization analyzers are the same, the correlation is, within experimental error, perfect. In other words, a measurement of only one photon suffices to tell the experimenter what the polarization of the other photon is. At arbitrary angles, the correlation drops, but it is not zero. Realistic, local theories imply a limit, as expressed by Bell's inequality, to how strong the correlation can be. Quantum mechanics says the correlation can be higher.

The source of the correlations lies in


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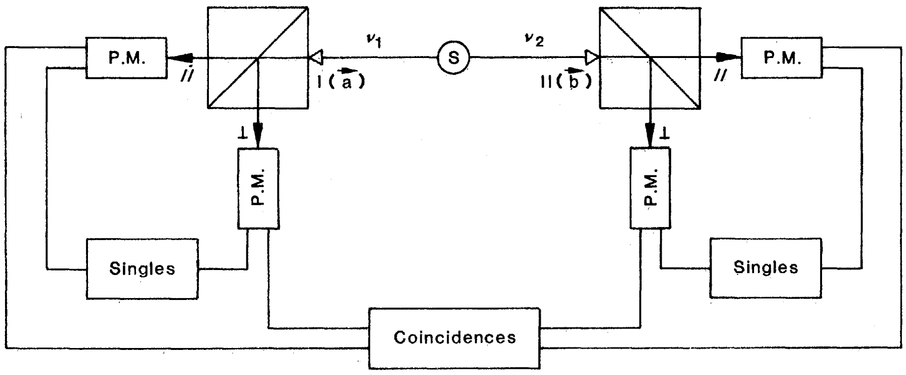


***Photon polarization correlation experiment***

*The source S is an atomic beam of calcium excited by absorption of light from two lasers. The two photons emitted by the calcium pass through the polarizing cubes and are registered by the photomultiplier tubes. The orientations* $\vec{a}$ *and* $\vec{b}$ *are selected by rotating the polarizing cubes* I *and* II *about the axis of the photon beams.* [*Adapted from* (*1*)]

the peculiar feature of quantum mechanics that one cannot measure arbitrarily accurately conjugate variables, such as position and translational momentum. The relevant variables of spin-½ particles for Bell's inequality are angular momentum components. One is allowed to know the total angular momentum of a particle and its component (projection) along one axis of a Cartesian coordinate system but not along the other two coordinates. A similar situation holds for the linear polarization of photons, where aligning a polarization analyzer in effect selects a component to be measured, but leaves the others alone.

Realism requires that the angular momentum components exist and have definite values whether or not they are measured. Moreover, locality implies that the choice of which component to measure for one particle ought not affect in any way the result of the measurement of any component of the other. Nonetheless, one can draw certain conclusions about the results of measurements. For example, if one measures an angular momentum component of the first particle, one knows what the result of a measurement of the same component of the second particle would have been, even though a different component was actually measured. Considerations such as these lead to Bell's inequality (*3*).

The higher correlation permitted by quantum mechanics can be explained in two ways. The first is that information is transmitted from one analyzer to the other faster than the speed of light, so that the setting of one analyzer somehow (no one knows how it might be done) influences the results of measurements made by the other analyzer. The second possibility is to discard the idea of realism. Neither alternative is particularly palatable.

Are there any loopholes by which to escape from having to make such an unhappy decision? The answer is yes.

The first escape hatch exists because of the inefficiencies of photodetectors. Not all photons are detected. The proof of Bell's inequality assumes that the photons actually measured are a faithful representation of all photons reaching the analyzers. But there is no foolproof way to demonstrate this, short of having very high efficiency detectors that register nearly every photon.

The first experiments to test Bell's inequality by means of photon polarization (by Stuart Freedman and Clauser at the University of California at Berkeley) correlation used a slightly different geometry and required a supplementary measurement. Simple polarization analyzers were used so that, given a particular orientation, only photons parallel to the analyzer reached the detector and were registered. The rate of photon detection with no polarizers in place then served as a kind of normalizing procedure. These results were in agreement with quantum mechanics. However, in 1974, Clauser, who had moved to the Lawrence Livermore National Laboratory, and Horne constructed a highly artificial realistic, local theory that succeeded in reproducing the experimental results obtained 2 years earlier by Freedman and Clauser. The model made essential use of the inefficiency of the detectors.

Aspect and his colleagues have improved on this and other previous experiments by constructing an analyzer that could pass photons of both parallel and perpendicular polarizations. The analyzers are polarizing cubes made of two prisms with coatings of dielectric thin films on the sides and then stuck together. In this way, a much larger fraction of the photons was detected, but there is still no way to be absolutely sure that there is not some bizarre difference between detected and undetected photons that makes Bell's inequality invalid and thereby removes the contradiction between quantum mechanics and realistic, local theories.

A year ago, Shimony and Tak Kui Lo, now at Oklahoma State University, proposed an experiment involving pairs of sodium atoms (*4*). Rather than photon polarization, it would be the sodium electron spin angular momentum that is detected. The analysis and detection processes using Stern-Gerlach analyzers are highly efficient and no supplementary assumptions are required, so this experiment could block the first loophole. According to Shimony, no one is attempting it, in part because it is so difficult.

The second loophole is that the orientations of the polarization analyzers are set well in advance of the arrival of the photons. Therefore, there is ample time for some (unknown) signal to travel at less than light speed from one analyzer to the other and thereby influence subsequent events. The analyzers in the present French experiment are 13 meters apart, so there is no chance that the quantum mechanical wave functions of the two photons are overlapping and could in that way influence one another. Any other signal would be highly mysterious but cannot be ruled out.

In 1976, Aspect proposed an experiment using acousto-optic devices that could randomly and rapidly switch the photons between two analyzers of different orientations for each of the two photon beams (*5*). Voltages applied to a crystal generate standing acoustic waves that then act as an adjustable diffraction grating for the incoming light. In this way, any signal traveling between the commutators and containing information about the switching direction would have to travel faster than light to influence any measurements.

The present French publication is in effect a progress report toward the implementation of this proposal. It now seems that all the ingredients of the experiment are in place and working, including the acousto-optic switches. Results are expected "soon," according to one source.—ARTHUR L. ROBINSON

**References**

1. A. Aspect, P. Grangier, G. Rogier, *Phys. Rev. Lett.* **49**, 91 (1982). A similar experiment, begun by V. A. Rapisarda and his colleagues, is in progress at the University of Catania in Italy.
2. J. Clauser and A. Shimony, *Rep. Prog. Phys.* **41**, 1881 (1978).
3. B. d'Espagnat, *Sci. Am.* **241**, 158 (November 1979).
4. T. K. Lo and A. Shimony, *Phys. Rev. A* **23**, 3003 (1981).
5. A. Aspect, *Phys. Rev. D* **14**, 1944 (1976).