Bell's inequality test: more ideal than ever

Alain Aspect

The experimental violation of Bell's inequalities confirms that a pair of entangled photons separated by hundreds of metres must be considered a single non-separable object — it is impossible to assign local physical reality to each photon.

Bell's theorem[1], formulated in 1964, is one of the profound scientific discoveries of the century. Based on the Einstein, Podolsky and Rosen (EPR) *gedanken*, or thought, experiment[2], it shifted the arguments about the physical reality of quantum systems from the realm of philosophy to the domain of experimental physics. For almost three decades, experimental tests[3] of Bell's inequalities have evolved closer and closer to the ideal EPR scheme. An experiment at the University of Innsbruck[4] has, for the first time, fully enforced Bell's requirement for strict relativistic separation between measurements.

It all started when Einstein *et al.* pointed out that for certain quantum states (described almost simultaneously by Schrödinger, who coined the expression 'quantum entanglement'), quantum mechanics predicts a strong correlation between distant measurements. Figure 1 shows a modern version of the EPR situation, where a pair of entangled photons ν_1 and ν_2 are travelling in opposite directions away from a source. Results of polarization measurements with both polarizers aligned are 100% correlated. That is, each photon may be found randomly either in channel + or − of the corresponding polarizer, but when photon ν_1 is found positively polarized, then its twin companion ν_2 is also found positively polarized. Because no signal can connect the two measurements if it travels at a velocity less than or equal to the speed of light, *c*, and because the choice of the direction of analysis can be made at the very last moment before measurement while the photons are in flight, how — argued Einstein — could one avoid the conclusion that each photon is carrying a property, determining the polarization outcome for any direction of analysis?

This seemingly logical conclusion provides a simple image to understand the correlations between distant and simultaneous measurements. But it means specifying supplementary properties ('elements of reality' in the words of Einstein) beyond the quantum-mechanical description. To the question "Can a quantum-mechanical description of physical reality be considered complete?"[2] Einstein's answer was clearly negative, but this conclusion was incompatible with the 'Copenhagen interpretation' defended by Bohr, for whom the quantum-mechanical description was the ultimate one[5]. This debate between Einstein and Bohr lasted until the end of their lives. As it was, it could hardly be settled, because there was no apparent disagreement on the correlations predicted for an EPR *gedanken* experiment. The point under discussion was the world-view implied by the analysis of the situation.

Bell's theorem changed the nature of the debate. In a simple and illuminating paper[1], Bell proved that Einstein's point of view (local realism) leads to algebraic predictions (the celebrated Bell's inequality) that are contradicted by the quantum-mechanical predictions for an EPR *gedanken* experiment involving several polarizer orientations. The issue was no longer a matter of taste, or epistemological position: it was a quantitative question that could be answered experimentally, at least in principle.

Prompted by the Clauser–Horne–Shimony–Holt paper[6] that framed Bell's inequalities in a way better suited to real experiments, a first series of tests[7], using photon pairs produced in atomic radiative cascades, was performed in the early 1970s at Berkeley, Harvard and Texas A&M. Most results agreed with quantum mechanics, but the schemes used were far from ideal; in particular, the use of single-channel polarizers only gave access to the + outcome. Progress in laser physics and modern optics led to a new generation of experiments carried out by colleagues and myself at Orsay in the early 1980s. They were based on a highly efficient source of pairs of correlated photons, produced by non-linear laser excitations of an atomic radiative cascade. An experiment involving two-channel polarizers, as in the ideal EPR *gedanken* experiment, gave an unambiguous violation of Bell's inequalities by tens of standard deviations, and an impressive agreement with quantum mechanics[8].

A third generation of tests, begun in the late 1980s at Maryland and Rochester[9,10], used nonlinear splitting of ultraviolet photons to produce pairs of correlated EPR photons. With such pairs, measurements can bear either on discrete variables such as polarization or spin components, as considered by Bell, or on continuous variables of the type originally considered by Einstein, Podolsky and Rosen, and studied at Caltech[11]. A remarkable feature of such photon sources is the production of two narrow beams of correlated photons that can be fed into two optical fibres, allowing for tests with great distances between the source and the measuring apparatus, as demonstrated over four kilometres in Malvern[12] and over tens of kilometres in Geneva[13].

The experimenters at Innsbruck[4] used this method to address a fundamental point raised by Bell. In the experiment shown in Fig. 1, where the polarizers' orientations are kept fixed during a run, it is possible to rec-

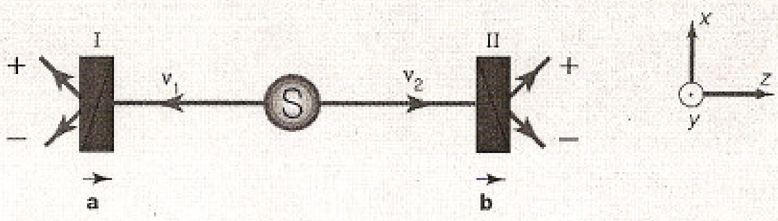

Figure 1 Einstein–Podolsky–Rosen *gedanken* experiment with photons. The two photons, ν_1 and ν_2, are analysed by the linear polarizers I and II, which make polarization measurements along $\vec{a}$ and $\vec{b}$ perpendicular to the z axis. Each measurement has two possible outcomes, + or −, and one can measure the probabilities of single or joint measurements at various orientations $\vec{a}$ and $\vec{b}$. For an entangled EPR state, violation of a Bell's inequality indicates that the strong correlations between the measurements on the two opposite sides cannot be explained by an image '*à la* Einstein' involving properties carried along by each photon. In the Innsbruck experiment[4], any possibility of communication between the polarizers, at a velocity less than or equal to that of light, is precluded by random and ultrafast switching of the orientations of the polarizers, separated by a distance of 400 m. On each side, a local computer registers the polarizer orientation and the result of each measurement, with the timing monitored by an atomic clock. Data are gathered and compared for correlation measurements after the end of a run.

oncile the quantum mechanical predictions and Einstein's conceptions by invoking a possible exchange of signals between the polarizers. To avoid this loophole, Bell stressed the importance of experiments "in which the settings are changed during the flight of the particles"[1], so that any direct signal exchange between polarizers would be impossible, provided that the choice of orientations is made randomly in a time shorter than the flight time of the particle or photon, to ensure that relativistic separation is enforced.

Prompted by Bell's remark, a first step towards the realization of this ideal scheme[14] found a violation of Bell's inequality with rapidly switched polarizers, but the polarizer separation (12 m) was too small to allow for a truly random resetting of the polarizers. With a separation of 400 m between their measuring stations, the physicists of Innsbruck[4] have 1.3 μs to make random settings of the polarizer and to register the result of the measurement, as well as its exact timing monitored by a local rubidium atomic clock. It is only at the end of the run that the experimentalists gather the two series of data obtained on each side, and look for correlations. The results, in excellent agreement with the quantum mechanical predictions, show an unquestionable violation of Bell's inequalities[4].

This experiment is remarkably close to the ideal *gedanken* experiment, used to discuss the implications of Bell's theorem. Note that there remains another loophole, due to the limited efficiency of the detectors, but this can be closed by a technological advance that seems plausible in the foreseeable future, and so does not correspond to a radical change in the scheme of the experiment. Although such an experiment is highly desirable, we can assume for the sake of argument that the present results will remain unchanged with high-efficiency detectors.

The violation of Bell's inequality, with strict relativistic separation between the chosen measurements, means that it is impossible to maintain the image '*à la* Einstein' where correlations are explained by common properties determined at the common source and subsequently carried along by each photon. We must conclude that an entangled EPR photon pair is a non-separable object; that is, it is impossible to assign individual local properties (local physical reality) to each photon. In some sense, both photons keep in contact through space and time.

It is worth emphasizing that non-separability, which is at the roots of quantum teleportation[15], does not imply the possibility of practical faster-than-light communication. An observer sitting behind a polarizer only sees an apparently random series of − and + results, and single measurements on his side cannot make him aware that the distant operator has suddenly changed the orientation of his polarizer. Should we then conclude that there is nothing remarkable in this experiment? To convince the reader of the contrary, I suggest we take the point of view of an external observer, who collects the data from the two distant stations at the end of the experiment, and compares the two series of results. This is what the Innsbruck team has done. Looking at the data a posteriori, they found that the correlation immediately changed as soon as one of the polarizers was switched, without any delay allowing for signal propagation: this reflects quantum non-separability.

Whether non-separability of EPR pairs is a real problem or not is a difficult question to settle. As Richard Feynman once said[16]: "It has not yet become obvious to me that there is no real problem ... I have entertained myself always by squeezing the difficulty of quantum mechanics into a smaller and smaller place, so as to get more and more worried about this particular item. It seems almost ridiculous that you can squeeze it to a numerical question that one thing is bigger than another. But there you are — it is bigger...". Yes, it is bigger by 30 standard deviations. ☐

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12.2 BELL'S THEOREM

Griffiths

Einstein, Podolsky, and Rosen did not doubt that quantum mechanics is *correct*, as far as it goes; they only claimed that it is an *incomplete* description of physical reality: The wave function is not the whole story—some *other* quantity, λ, is needed, in addition to Ψ, to characterize the state of a system fully. We call λ the "hidden variable" because, at this stage, we have no idea how to calculate or measure it.[3] Over the years, a number of hidden variable theories have been proposed, to supplement quantum mechanics;[4] they tend to be cumbersome and implausible, but never mind—until 1964 the program seemed eminently worth pursuing. But in that year J. S. Bell proved that *any* local hidden variable theory is *incompatible* with quantum mechanics.[5]

Bell suggested a generalization of the EPR/Bohm experiment: Instead of orienting the electron and positron detectors along the *same* direction, he allowed them to be rotated independently. The first measures the component of the electron spin in the direction of a unit vector **a**, and the second measures the spin of the positron along the direction **b** (Figure 12.2). For simplicity, let's record the spins in units of $\hbar/2$; then each detector registers the value $+1$ (for spin up) or -1 (spin down), along the direction in question. A table of results, for many π^0 decays, might look like this:

electron	positron	product
+1	−1	−1
+1	+1	+1
−1	+1	−1
+1	−1	−1
−1	−1	+1
⋮	⋮	⋮