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Aspect Experiment

A.J. Leggett

In 1965, John S. Bell proved a celebrated theorem [1] which essentially states that no theory belonging to the class of "objective local theories" (OLT's) can reproduce the experimental predictions of quantum mechanics for a situation in which two correlated particles are detected at mutually distant stations (► Bell's Theorem). A few years later Clauser et al. [2] extended the theorem so as to make possible an experiment which would in principle unambiguously discriminate between the predictions of the class of OLT's and those of quantum mechanics, and the first experiment of this type was carried out by Freedman and Clauser [3] in 1972. This experiment, and (with one exception) others performed in the next few years confirmed the predictions of quantum mechanics. However, they did not definitively rule out the class of OLT's, because of a number of "loopholes" (► Loopholes in Experiments). Of these various loopholes, probably the most worrying was the "locality loophole": a crucial ingredient in the definition of an OLT is the postulate that the outcome of a measurement at (e.g.) station 2 cannot depend on the nature of the measurement at the distant station 1 (i.e., on the experimenter's choice of which of two or more mutually incompatible measurements to perform). If the space-time interval between the "event" of the choice of measurement at station 1 and that of the outcome of the measurement at station 2 were spacelike, then violation of the postulate under the conditions of the experiment would imply, at least prima facie, a violation of the principles of special relativity, so that most physicists would have a great deal of confidence in the postulate. Unfortunately, in the experiments mentioned, the choice of which variable to measure was made in setting up the apparatus (polarizers, etc.) in a particular configuration, a process which obviously precedes the actual measurements by a time of the order of hours; since the spatial separation between the stations was only of the order of a few meters, it is clear that the events of choice at 1 and measurement at 2 fail to meet the condition of spacelike separation by many orders of magnitude, and the possibility is left open that information concerning the setting (choice) at station 1 has been transmitted (subluminally) to station 2 and affected the outcome of the measurement there. While such a hypothesis certainly seems bizarre within the framework of currently accepted physics, the question of the viability or not of the class of OLT's is so fundamental an issue that one cannot afford to neglect it completely.

In this situation it becomes highly desirable, as emphasized by Bell in his original paper, to perform an experiment in which the choice of what to measure at station 1 is made "at the last moment", so that there is no time for information about this choice to be transmitted (subluminally or luminally) to station 2 before the outcome of the measurement there is realized. Of course, whether or not this condition is fulfilled in any given experiment depends crucially on exactly at what stage the "realization" of a specific outcome is taken to occur, and this question immediately gets us into the fundamental problem of measurement in quantum mechanics (► Measurement Theory); however, most discussions of the incompatibility of OLT's and quantum theory in the literature have been content to assume that the realization occurs no later than the first irreversible processes taking place in the macroscopic measuring device.(For example, in a typical photomultiplier it is assumed to take place when the photon hits the cathode and ejects the first electron, since in practice any processes taking place thereafter are irreversible). Although this assumption is certainly questionable, for the sake of definiteness it will be made until further notice.

The first experiment to attempt to evade the locality loophole was that of Aspect et al. [4] in 1982, and subsequent experiments which continue this approach are often referred to as "Aspect-type". In some sense these experiments are a sub-class of the more general category of "delayed-choice" experiments ► Delayed-Choice Experiment), but they have a special significance in their role of attempting to exclude the class of OLT's. In the original experiment [4], the distance between the detection stations is about 12 m, corresponding to a transit time for light of 40 nsec. At each station, the "switch" which decides which of the two alternative measurements to make is an acousto-optical device; in each case two electro-acoustical transducers, driven in phase, create ultrasonic standing waves in a slab of water through which the relevant photon must pass, with a period of about 25 MHz (the frequency is different for the two stations). The periodic density variation in the wave acts as a diffraction grating: If a given photon ► wave packet (length in time $\sim$5 nsec) arrives at (say) station 1 when the wave has a node (i.e., the density and hence dielectric constant of the water is uniform) it is transmitted rectilinearly through the slab and enters a polarizer set in direction a; if on the other hand it arrives at an antinode (periodic density variation) it undergoes Bragg diffraction and is directed into a polarizer set at a'. (See Fig. 1). Photons (► light quantum) incident at intermediate phases of the wave are deflected into neither polarizer and thus missed in the counting. The period of switching between the alternative choices (a quarter period of the transducers) is about 10 nsec., short compared to the transit time of light between the stations. To the extent, then, that one can regard the switching as a "random" process, the locality loophole is blocked. The data obtained in ref. [4] violate the OLT predictions by 5 standard deviations.

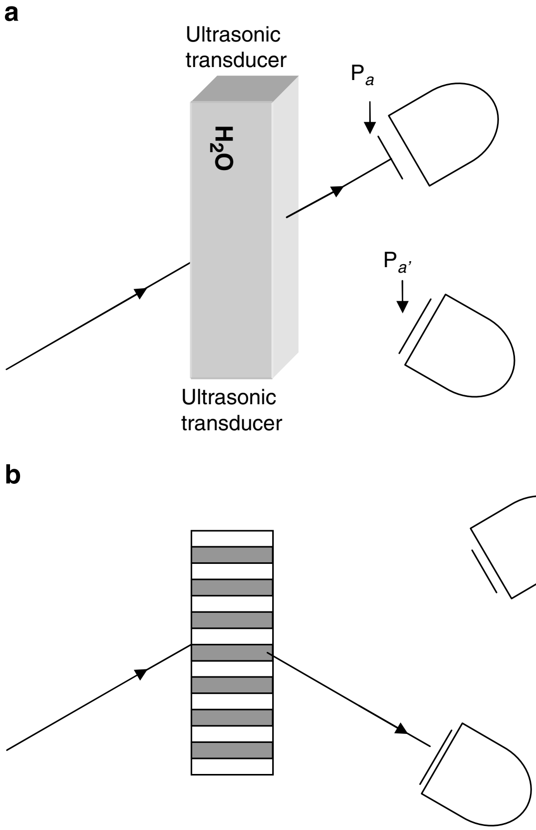

Fig. 1 Schema of switching devices in Aspect experiment. P_a ($P_{a'}$) are polarisers with transmission axis $\boldsymbol{a}$ (**a**). When a photon arrives at time on ultrasonic cycle when density of H_2O is constant, it is directed into P_a; (**b**) if it arrives at a maximum of the standing wave, into $P_{a'}$

Is the switching in fact a truly random process? On the one hand, since the transducer pairs are driven by different generators at different frequencies, there is no correlation between the choices made at the two stations, and as we have seen no time for information about the choice itself to be transmitted between them. On the other hand, since the driving at each station separately is periodic, a sufficiently determined advocate of OLT's might argue that station 2 has the information to predict what the setting at station 1 will be at a given time in the future and to make arrangements accordingly (and of course vice versa). Thus, while the experiment of ref. [4] is clearly a major advance on the original Freedman-Clauser one, not everyone was convinced that it had definitively blocked the locality loophole.

Of the various Aspect-type experiments performed subsequently to 1982, probably the most notable is that of Weihs et al. [5]. This experiment used a much longer baseline, around 400 m, and the choice of measurement was made by a quantum random number generator (QRNG), with a total switching time of less than 100 nsec.

A further feature of this experiment, unique up to now among the whole class of "Bell's theorem" experiments, is that instead of being channelled to a central coincidence counter the detection outcomes are recorded in situ and compared, with the help of accurate timing, only hours or days later (so that, coming back to the question of the time of "realization", its postponement until the time of comparison, which is not totally implausible in other experiments, would in this case seem distinctly unnatural). The duration of the registration process was such that it is completed well within the signal transit time. The data obtained are consistent with the predictions of quantum mechanics and violate those of the class of OLT's by 30 standard deviations.

One further experiment which has some significance in the present context is that of Tittel et al. [6]. Although there was no in-situ recording, this is otherwise similar in spirit to that of ref. [5], with an even longer base-line (10 km); the difference is that the role of the QRNG which controls the choice of measurement is played by the measured photon itself (it impinges on a beam splitter where the output beams correspond to different choices). Once more good agreement with the predictions of quantum mechanics is obtained.

In the light of these experiments, any attempt to continue to exploit the locality loophole to defend a theory of the OLT class would have either to deny that the QRNG's used work in a genuinely random way, or postpone the realization process for at least 1.3 microsec after the photon enters the photomultiplier (the signal transit time in the experiment of Weihs et al.). A truly definitive blocking of this loophole would presumably require that the detection be directly conducted by two human observers with a spatial separation such that the signal transit time exceeds human reaction times, a few hundred milliseconds (i.e., a separation of several tens of thousand kilometers). Given the extraordinary progress made in quantum communication in recent years, this goal may not be indefinitely far in the future. In the meantime, a small step in this direction might be taken by repeating the experiment of Weihs et al. with inspection of the outcomes by independent human observers before they are correlated, something which was not done in ref. [5].[1]

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[1] This work was supported by the National Science Foundation under grant no. NSF-EIA-01-21568.

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Asymptotic Freedom

See ► Color Charge Degree of Freedom in Particles Physics; QCD; QFT.

Atomic Model

See also: ► Bohr's Atomic Model; Rutherford Atom.

Atomic Models, J.J. Thomson's "Plum Pudding" Model

Klaus Hentschel

In 1897, Joseph John Thomson (1856–1940) had announced the discovery of a corpuscle. Others soon called it ► electron, despite Thomson's stubborn preference for his original term, borrowed from Robert Boyle (1627–91) to denote any particle-like structure. Very soon afterwards, Thomson began to think about how to explain the periodicity of properties of the chemical elements in terms of these negatively charged corpuscles as atomic constituents. Chemical properties would thus have to depend on the number and constellations of these corpuscles inside the atom. They would have to have stable positions in it, bound by electrostatic and possibly kinetic forces. Because under normal conditions chemical atoms are electrically neutral, the total electric charge of all these negatively charged electrons had to be compensated for by an equal amount of positive charge. For Thomson it was natural to

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Compendium of Quantum Physics
Concepts, Experiments, History and Philosophy
Greenberger, D.; Hentschel, K.; Weinert, F. (Eds.)
2009, XVI, 901 p., Hardcover
ISBN: 978-3-540-70622-9