Bell's theorem and delayed determinism

J. D. Franson
Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland 20707
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The most recent experiment by Aspect, Dalibard, and Roger does not appear to rule out a class of theories in which the outcome of an event is not determined until some time after its occurrence. This class of theories includes not only the quantum theory but various local, realistic theories as well.

In his classic paper, Bell[1] showed that there are measurable differences between the quantum theory and any local theory. His proof was based upon an assumed locality condition, according to which the results obtained from one measurement device must be independent of the setting of a distant measurement device. There has always been a question, however, as to the experimental arrangements required in order to satisfy Bell's locality condition. For example, what separation is required between two photon detectors in order for them to be considered "distant"? Bell suggested[1] that the ideal experiment would be one in which the settings of the detectors could be changed during the flight of the particles, so as to rule out any interaction or exchange of information at velocities less than or equal to the speed of light.

Such an experiment has recently been completed by Aspect, Dalibard, and Roger.[2] High-speed optical switches were used to direct each photon toward one of two polarizers with different orientations, so that the settings of the measurement devices were effectively selected within a very short time interval. Although there has been some concern over the efficiency of the switches and other factors,[3] the experiment has been widely accepted as providing conclusive evidence against all local, realistic theories.[4]

In this paper, it will be argued that the experiment by Aspect, Dalibard, and Roger does not rule out a certain class of theories in which the outcome of an event is not determined until some time after the event has already occurred. This class of theories includes not only the quantum theory but various local theories as well. From a classical point of view, the optical switches and measurement devices must determine whether or not a photon has been absorbed in a given detector at the same instant such an event would have occurred. But if the outcomes of such events are not actually determined until some later time, then information regarding the orientations of the polarizers could conceivably be exchanged at velocities less than that of light and used during the subsequent determination process. Although such theories may seem counterintuitive, this should not preclude their consideration, particularly when the quantum theory itself is based upon similar principles. With an appropriate reinterpretation, some of these theories may include hidden variables and are then local, realistic theories, as will be discussed in more detail near the end of the paper.

For the purposes of this discussion, an *event* will be defined as any process which is known[5] to be completed in some finite time, such as the emission of a photon by an excited atom. An event will be referred to as having *occurred* once sufficient[5] time has elapsed for the process in question to have been completed. The various *outcomes* of an event will refer to the possible values of the parameters describing the system which can be measured after the occurrence of the event. The outcome of an event will be referred to as being *determined* at any given time if a definite value can be associated with each of the measurable parameters describing the system. The concept that the outcome of an event may not be determined until some time after its occurrence is not contradictory if it is assumed, as in the quantum theory, that the properties of a system are fundamentally dependent upon their measurement or observation. An alternative interpretation can be made in the case of hidden-variable theories, but a discussion of that possibility will be more appropriate at a later point.

Before considering the experiment by Aspect, Dalibard, and Roger, it may be useful to discuss a simple example taken from the quantum theory. Consider a particle incident upon two slits and producing the well-known diffraction pattern. Suppose that the particle was emitted within a reasonably short time or is localized into a wave packet of limited spatial extent by some other means. The time at which the particle must pass through the slits can thus be known to within some relatively small uncertainty, and it is possible to consider the state of the system at some later time. In the quantum theory, there is a nonzero probability amplitude ψ_i that the particle passed through slit i, and interference between these amplitudes produces the interference pattern. The question of which slit the particle passed through is evidently not determined[6] until after that event has already occurred, if at all.[7] Both amplitudes ψ_i exist simultaneously and have measurable effects which would not have been the same if only one had existed after the occurrence of the event.

The example discussed above is, of course, well known. The situation becomes more interesting, however, if theories more general than the quantum theory are considered. The general time development of probability amplitudes ψ_i for the possible outcomes of an event will be of particular interest. For lack of a better term, a theory in which the outcome of an event is not determined until some time after its occurrence, and in which there are measurable effects due to this indeterminacy, will be referred to as a delayed determinism theory.

In the quantum theory, the subsequent time development of the ψ_i is relatively simple but abrupt. If an appropriate measurement is made at some later time, then one of the ψ_i is set to unity and all of the other ψ_i instantaneously become zero. This reduction of the wave packet can produce instantaneous changes in the wave function or field describing a particle at locations which are distant from the measurement device, and is the source of the nonlocality inherent in the quantum theory.

Various attempts[8,9] have been made to develop theories incorporating an alternative measurement process which takes place over a nonzero time interval and whose effects propagate at the speed of light, thus maintaining locality. States describing the measurement device might also be included as part of the system as a whole. For example, one could consider a theory which retains the probability amplitudes of the quantum theory, but in which their time development after the occurrence of the event is given by

$$\frac{d\psi_i}{dt}=\sum_j F_{ij}\psi_j+g_i(t)\ . \tag{1}$$

Here $g_i(t)$ is a random driving function (noise) and the coefficients F_{ij} may be functions of the ψ_j themselves. If the ψ_i also include probability amplitudes for the various possible final states of the measurement device, then it may be possible to develop nonlinear equations in which the amplitude for one final state eventually approaches unity while all the others approach zero, depending upon the values of the $g_i(t)$ encountered. Such a theory would produce a definite outcome for each measurement, while avoiding nonlocal changes in the fields.

The actual development of local theories incorporating such a measurement process would be an interesting subject in itself, but is not necessary in order to make the main point of this paper. Returning to the experiment by Aspect, Dalibard and Roger, the events of interest are not single-particle events, but consist of the simultaneous detection of two photons which have passed through two polarizers. One can then consider probability amplitudes for the pair of photons to have been detected in the various detectors at various times. The effect of the optical switches is to ensure that these events occur within some relatively well-defined time interval, just as the passage of a particle through two slits in the earlier example can be made to occur at some well-defined time. The possibility being suggested here is that the probability amplitudes $\psi_i(t)$ for such events may all continue to be nonzero for some time after the event has occurred, and that their time development may be governed by some equation similar to that of Eq. (1). If a sufficiently large amount of time elapses during this process, information regarding the orientation of the polarizers could be effectively exchanged at velocities less than that of light and the final outcome could perhaps give a coincidence rate as predicted by the quantum theory.

In a local theory of this kind, the question of whether or not a coincidence count had been recorded in a particular counter would not be determined until after that event would have already occurred. Although this may seem counterintuitive, it is no more so than the quantum-mechanical assertion that the passage of a particle through one or the other of two slits is not determined[6] until after the particle has already passed through them. Perhaps the primary difference between the standard quantum-mechanical description of double-slit diffraction and what is being proposed here is that the probability amplitudes would now have to describe the states of the measurement device (i.e., the coincidence circuit) and not just the photons or other particles. Thus a superposition of states describing a macroscopic system over a microscopic time interval would be required if a local theory were to be made to agree with the results of the experiment by Aspect, Dalibard, and Roger in this way. There would appear to be no fundamental difference, however, between superpositions of states describing single particles, pairs of photons, or macroscopic measurement devices.[10] If locality were hypothetically assumed to be a valid law of nature, then the experiment of Aspect, Dalibard, and Roger could be viewed as an experimental demonstration[11] of the superposition of macroscopic states over microscopic time intervals.

The time interval over which the probability amplitudes discussed above may simultaneously exist and interact in the experiment by Aspect, Dalibard, and Roger could conceivably be comparable to the 89-nsec lifetime[12] of the excited atomic state which produces the pair of photons. If the photon emission time remains indeterminate for that length of time, then it is plausible that the final outcome of the event may remain indeterminate for a comparable amount of time. Alternatively, if the process under consideration is taken to include the excitation of the atom as well as the emission of the photons, then the indeterminacy could conceivably persist for time intervals comparable to the coherence time of the lasers used to excite the source. There is, of course, no evidence (other than, perhaps, this experiment) that such probability amplitudes exist simultaneously over these time intervals; on the other hand, there appears to be no logical reason why they could not.

It may be worth noting that the interpretation of theories of this kind need not be probabilistic. The ψ_i could be interpreted as deterministic in nature if the driving terms $g_i(t)$ were considered to be determined but unknown, and if Eq. (1) or some similar mechanism were to cause all but one of the ψ_i to become zero after a macroscopic time had elapsed. The results of a measurement would then be physically determined in advance, although an experimenter could not determine the results for himself until some later time. The intermediate situation, with many nonzero ψ_i's, would then describe the dynamics of the system, which may not be directly observable during the microscopic time interval over which the measurement process occurs. From this point of view, the fact that a photomultiplier tube produces a very brief pulse may only reflect the observable properties of the detector; the actual measurement process, including the absorption of a photon, may not be directly observable and may take place over a much longer period of time. Hidden-variable theories of this kind are local, realistic[13] theories.

In hidden-variable theories of this kind, the outcome of an event would have been completely determined by various factors, but those factors would have continued to influence that outcome during a time interval following the apparent time of occurrence of the event. One way to interpret such a situation would be to continue to define certain events as essentially instantaneous occurrences, since that is what is often observed, and to assume that the system has no definite properties until the measurement process has been completed, as in the quantum theory. But an alternative interpretation would be to abandon the idea of there being discrete events, and to view the entire situation, including the measurement apparatus, as a continuous process. Both interpretations would require a departure from our ordinary view of reality, since the operation of the measurement apparatus could no longer be described as a sequence of classical events.

It might be asked whether or not there are any experimental situations in which Bell's locality condition would be satisfied, despite the possibilities discussed above. An argument based on time-reversal invariance[14] suggests that this would be the case if the actual separation of the photon counters were sufficiently large, and if the light source were of sufficiently low intensity. The preliminary results from a single-photon interferometer experiment[15] satisfying these conditions are in apparent agreement with the requirements of all local theories.

In summary, it is not evident that the experiment of Aspect, Dalibard, and Roger rules out all local theories in which the outcome of an event is not determined until after its apparent time of occurrence. The usual interpretation of the results of the experiment are based on a classical[10] view of the limitations imposed by the operation of the optical switches and measurement devices. On an intuitive basis, theories of this kind may not seem to merit serious consideration. Nevertheless, local theories incorporating delayed determinism are a logical possibility that should be considered.

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[1]J. S. Bell, Physics **1**, 195 (1964). The possibility of varying the settings of the measurement devices during the flight of the particles had previously been suggested by D. Bohm and Y. Aharonov, Phys. Rev. **108**, 1070 (1957).

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

[3]The author recently presented a local theory [Conference on Fundamental Questions in Quantum Mechanics, State University of New York at Albany, 1984 (Gordon and Breach, New York, to be published)] which was in good agreement with the published results of Aspect, Dalibard, and Roger. This theory assumed that there may be significant correlations between the polarizations of two photons emitted by different atoms in the light source. More recent measurements in which the accidental counting rate was reduced [A. Aspect (private communication)] cannot be accounted for by this theory. There has also been some concern over the fact that the optical switching was periodic, rather than randomized, and allowed a photon to travel toward either polarizer during a substantial portion of the switching cycle.

[4]A. L. Robinson, Science **219**, 40 (1983); F. Rohrlich, *ibid*. **221**, 1251 (1983).

[5]In any reasonable sense, one can ensure that a process of interest has been completed by allowing a sufficiently large amount of time for it to occur. For example, the emission of a photon by an excited atom can be assumed to have been completed after a large number of atomic lifetimes. The assumption (or self-consistent derivation) that certain processes can be completed in a finite time interval should, however, be included with the other assumptions inherent in theories of the kind discussed in the text.

[6]In general, the word *determine* has two distinct meanings: (a) to fix or select the outcome of an event or (b) to obtain definite knowledge of the outcome of an event without influencing it. In most instances in the text, the choice of one meaning or the other is simply a matter of interpretation. It is the author's opinion that a physical theory consists of a set of equations giving definite experimental predictions, and that the various possible interpretations of a given theory are of no physical relevance. For this reason, no attempt will be made here to distinguish between the possible meanings of the word *determine;* the standard interpretation of the quantum theory may, however, require one or the other meaning.

[7]A determination of which slit the particle had passed through would, of course, destroy the interference pattern. But in the quantum theory, both probability amplitudes are still assumed to exist simultaneously until such a measurement is made.

[8]P. Pearle, Int. J. Theor. Phys. **18**, 489 (1979); Phys. Rev. D **29**, 235 (1984).

[9]D. Leiter, in Conference on Fundamental Questions in Quantum Mechanics (Ref. 3).

[10]The measurement device is described classically in the quantum theory. This would seem to be necessary if the relevant dynamics of the measurement device were directly observable by the experimenter. But the processes occurring in a measurement which takes place in a few nanoseconds are not directly observable by the experimenter, and in such a case it does not seem logically necessary that the measurement device be described classically, rather than by probability amplitudes.

[11]It may be worth noting that experiments intended to determine whether a superposition of macroscopic states occurs in superconducting rings are in progress. See, for example, W. den Boer and R. de Bruyn Ouboter, Physica **98B**, 185 (1980); R. F. Voss and R. A. Webb, Phys. Rev. Lett. **47**, 265 (1981).

[12]A. Aspect, C. Imbert, and G. Roger, Opt. Commun. **34**, 46 (1980).

[13]Realism has been defined as "a philosophical view, according to which external reality is assumed to exist and have definite properties, whether or not they are observed by someone" [J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1881

(1978)]. Hidden-variable theories of the kind discussed in the text are thus realistic theories, since any measurable quantity has a definite (and predetermined) value. The realism of the theory is not affected by the fact that a nonzero time interval may be required to actually measure such quantities, nor by the way in which the hidden-variable theory represents them.

[14] J. D. Franson, Phys. Rev. D **26**, 787 (1982).
[15] J. D. Franson and K. A. Potocki, Bull. Am. Phys. Soc. **28**, 26 (1983); Johns Hopkins APL Technical Digest **5**, 305 (1984).