International Journal of Theoretical Physics, Vol. 22, No. 4, 1983

Bell's Theorem and Backwards-in-Time Causality

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Received February 19, 1982

Bell has shown that quantum mechanics is incompatible with the notion of locality. The present paper begins by considering the possibility of invoking backwards-in-time causality to explain this violation of locality. This then leads to an examination of the possible relevance of backwards-in-time causality to measurement outcomes in general. It is found that the situations in which it could be involved are limited owing to causality paradoxes.

1. INTRODUCTION

It has been proved by J. S. Bell that some of the predictions of quantum mechanics are not compatible with the notion of locality[1] (Bell, 1964). By "locality" Bell means the requirement that the outcome of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past. As a result of Bell's proof, a number of experiments have actually been performed (Clauser and Shimony, 1978) to decide between quantum mechanics and local theories, and the results appear to confirm the validity of quantum mechanics.

Bell considers an unstable system of two spin-1/2 particles in a bound state with zero total spin. The bound state disintegrates without the total spin being changed and the two particles travel off in opposite directions so that they are soon widely separated and any interaction between them becomes negligible. If a spin measurement is performed on each particle, the spin components measured being in different directions, the probability of both particles yielding the same spin value is, according to quantum mechanics, equal to $\sin^2 \frac{1}{2}\theta$, where θ is the angle between the two directions.

[1] Bell's paper was particularly concerned with hidden variable theories, but it has since been realized that the argument is pertinent to any interpretation of quantum mechanics incorporating locality.

At first sight it would seem reasonable to assume that the outcome of a spin measurement on one of the particles is independent of which spin component (if any) of the other particle is measured. However, Bell has shown that, for an ensemble of such two-particle systems to satisfy this assumption, there would have to exist some choices of directions for which the above quantum mechanical prediction would not hold. Thus we have the surprising conclusion that two particles which have become widely separated in space are not independent: a measurement on one particle must, in certain circumstances, have an effect on the other particle's behavior.[2]

To explain the breakdown of locality one could postulate that the two particles communicate with each other by exchanging some kind of signals across the space separating them. This, however, seems a rather artificial resort. Moreover, in order to achieve consistency with the predictions of quantum mechanics, the signals would have to propagate instantaneously.

It is the purpose of the present paper to explore another possibility. The viewpoint to be expounded in the next section accepts Bell's nonlocality conclusion but suggests a physical "mechanism" for this effect. It is therefore local in the sense that it does not require any action at a distance.

2. BACKWARDS-IN-TIME CAUSALITY

The space-time picture of the thought experiment described above is given in Figure 1. The dashed line represents the world line of the initial spin-zero system. This system decays at D into the two spin-1/2 particles and measurements are subsequently performed on these at M_1 and M_2. Now, the type (i.e., the direction) of the spin measurement performed on the first particle at M_1 affects that particle's spin at later times. (More specifically, it affects the probabilities for the outcomes of subsequent measurements.) However, it is normally implicitly assumed that the type of measurement performed on a particle does not affect the values of any variables associated with the particle at times *earlier* than the measurement. The idea to be considered here is to dispense with this assumption and to postulate that a causal chain exists along the path M_1DM_2. If the measurement at M_1 has a bearing on the "state"[3] existing between M_1 and D, and

[2] It should be noted, however, that this effect cannot be used by observers to send information from one place to another: the quantum mechanical probabilities are such as to preclude this possibility (see, e.g., Eberhard, 1978). Likewise, in regard to the signals mentioned in the next paragraph and to the causal connections proposed later, it does not follow that these would provide a means for faster-than-light communication between observers (with the resulting causality paradoxes that would imply).

[3] The word "state" as used here is not referring to the quantum mechanical state vector for the two-particle system. Rather, it is assumed that there exist variables (and/or a state vector, perhaps) which are associated with an individual particle and which are not covered by the usual quantum mechanical description.

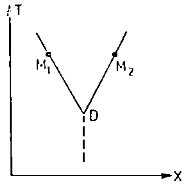


Fig. 1.

thence on the state between D and M_2, then clearly the nature of the measurement at M_1 can affect the result of the measurement at M_2. This idea[4] will now be pursued in more detail.

We must first make clear what is meant here by saying that one thing affects another. An event E_1 will be said to affect (or, in other words, to help determine) another event E_2 if E_2 can be changed (i.e., a different event occurs) by our choosing to change the nature of E_1. For example, by turning on a magnetic field we may affect the future history of an electron (i.e., where it goes to), but not its past history (i.e., where it comes from). Hence the magnetic field helps determine the future motion of the electron, but does not help determine its past motion.

In the ensuing discussion we will be concerned with the overall state of a particle at any particular time, this being (in addition to the usual state vector) the totality of all observable quantities having definite values at that time, together with any hidden variables (and/or hidden state vectors). Referring to Figure 1 again, that portion of the first particle's overall state between[5] D and M_1 which affects the outcome m_1 of measurement M_1 will be denoted by s_1, and that portion of the second particle's overall state between D and M_2 which affects the outcome m_2 of measurement M_2 will be denoted by s_2 (see Figure 2). We now postulate that there is also a portion of the first particle's overall state between D and M_1 which is affected by the choice of measurement at M_1 (and which in turn affects s_2) and that there is a portion of the second particle's overall state between D and M_2 which is affected by M_2 (and which affects s_1). These will be denoted by $\bar{s}_1$ and $\bar{s}_2$,

[4] It has been pointed out to the author by Dr. F. J. Belinfante that this possible explanation for the nonlocality demonstrated by Bell's thought experiment has also been considered by others (Costa de Beauregard, 1977 and 1979; Davidon, 1976; Eberhard, 1978; Rietdijk, 1978; Stapp, 1975). Upon examination, the work here is found to be not basically at variance with the particular models or views of these other authors. Indeed, the aim of the present research has been to formulate the backwards-in-time explanation in as general a way as possible and (in Section 3) to explore the causality implications that backwards-in-time effects would have for measurement outcomes in more general situations.

[5] For simplicity, we assume that the overall state of the first particle is the same at any instant between D and M_1 (and similarly for the second particle).

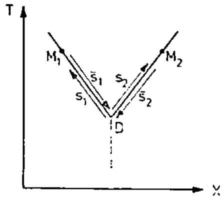


Fig. 2.

respectively.[6] Looking at Figure 2, it is clear that M_1 can affect m_2 via $\bar{s}_1$ and s_2, and that M_2 can affect m_1 via $\bar{s}_2$ and s_1. Hence, by invoking backwards-in-time causality, the ability of the two particles to influence one another is made understandable from a space-time viewpoint. This scheme constitutes a possible explanation for the quantum mechanical nonlocality found by Bell.[7]

3. FURTHER IMPLICATIONS

The above scheme suggests the possibility that the outcome of a measurement on a particle may be affected by its future state as well as by its past state. For example, the outcome of measurement M_1 on the first particle in Figure 2 may be partly determined by s_1 and partly determined by some portion of that particle's future state. This would not be possible in classical physics because, given the initial state of a classical particle and the interactions it will undergo, the final state can be predicted with certainty (i.e., classical mechanics is deterministic) and hence the result of a measurement on a classical particle cannot be affected by what the particle will encounter in the future because it is already completely determined by the past. In quantum mechanics, however, the result of a measurement is not uniquely determined by the known prior state (i.e., the state vector). In general, quantum mechanics can predict only the probability of any outcome. This leaves room for the nature of future measurements and interactions to have a bearing on the result. This will now be further explored.

Two consecutive measurements performed on a single particle are illustrated in Figure 3. The outcome of each measurement is assumed to be

[6]Thus, for example, $\bar{s}_1$ (and thence s_2) would be different if a different type of measurement were performed at M_1.

[7]It is worth noting that the possibility of instantaneous signals mentioned in Section 1 would also imply backwards-in-time causality: special relativity tells us that a signal propagating instantaneously relative to one reference frame must be traveling backwards in time relative to some other frames.

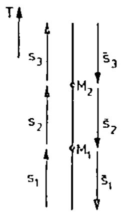


Fig. 3.

dependent on parts of both the prior and future states of the particle and on the type of measurement performed. For example, the outcome m_1 of measurement M_1 is determined by s_1, $\bar{s}_2$, and M_1 taken together. This will be written symbolically in the form

$$s_1, \bar{s}_2, M_1 \rightarrow m_1$$

It is possible that the internal state of the measuring apparatus may affect the outcome of the measurement it is performing. In the causal relationships listed below, both the type of measurement performed and the internal state of the apparatus will be accounted for by the one symbol (namely, M_1 or M_2). Referring to Figure 3 we have then

$$s_1, \bar{s}_2, M_1 \rightarrow m_1$$

$$s_2, \bar{s}_3, M_2 \rightarrow m_2$$

$$s_1, M_1 \rightarrow s_2$$

$$s_2, M_2 \rightarrow s_3$$

$$\bar{s}_3, M_2 \rightarrow \bar{s}_2$$

$$\bar{s}_2, M_1 \rightarrow \bar{s}_1$$

The above scheme has the desirable feature of being symmetric in time. Also, it provides the following possible explanation for why quantum mechanical phenomena appear indeterministic: The outcome of a measurement on a particle is, in this model, not completely determined by the particle's prior state. For a deterministic description, the particle's future state must also be taken into account. Since the future state cannot be known to us before the measurement, we are therefore limited to making statistical predictions on the basis of the particle's prior state.

There is, however, an argument which casts doubt upon this form of the scheme. Let us consider a Stern–Gerlach setup for determining the spin component of a spin-1/2 particle in, say, the x direction. An ensemble of particles passing through the magnetic field region in the apparatus will be split into two beams according to whether their x component of spin is $+\frac{1}{2}\hbar$ or $-\frac{1}{2}\hbar$. We assume that the outcome for an individual particle is affected by some portion f of the particle's subsequent overall state. It must then be possible to find two different f's which respectively yield the two different spin values as follows:

$$\begin{aligned} s, S_x, f_1 &\to +\tfrac{1}{2}\hbar \\ s, S_x, f_2 &\to -\tfrac{1}{2}\hbar \end{aligned} \tag{1}$$

where s denotes the relevant portion of the particle's prior state and S_x is the spin measurement. f is determined by the nature of the measurements and interactions in the particle's future, these being denoted collectively by F. Letting F_1 and F_2 denote future circumstances which correspond to f_1 and f_2, respectively, we have

$$F_1 \to f_1$$

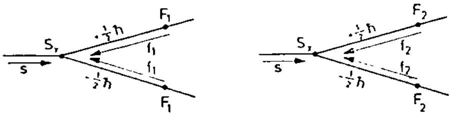
and

$$F_2 \to f_2$$

Applying relations (1) we may conclude that a particle with initial state s would follow the $+\frac{1}{2}\hbar$ path in the case of Figure 4a and would follow the $-\frac{1}{2}\hbar$ path in Figure 4b.

A paradox arises, however, if the particle is confronted with different future circumstances along the two paths. Whichever path the particle follows in Figure 5, its resulting f, determined by the future circumstances along that path, implies that it should have taken the other path. There seems to be no obvious way of escaping from this paradox without modifying the model.

In view of the above difficulty, a possible modification to our scheme will be considered. We retain the assumption that a measurement affects



a b

Fig. 4.

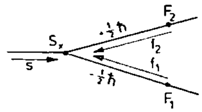


Fig. 5.

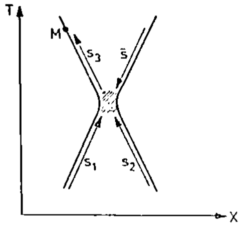


Fig. 6.

portions of both the future and past states of a particle, but require now that the outcome of a measurement be affected only by the particle's past state, not its future state. This then enables us to avoid the paradox without interfering with our explanation for Bell's nonlocality.

The new version is not symmetric in time and the effect of measurements and interactions on the past becomes important only in situations where the backwards-in-time portion of one particle's state can affect the forwards-in-time portion of another particle's state (as at point D in Figure 2). This, however, need not be a rare phenomenon. It could possibly occur whenever any two particles interact with each other. For example, in Figure 6 two particles interact and a measurement M is then performed on one of them. Under the scheme suggested here, the outcome m of the measurement would be affected by the backwards-in-time portion $\bar{s}$ of the other particle's state in the following way:

$$s_1, s_2, \bar{s} \rightarrow s_3$$

and then

$$s_3, M \rightarrow m$$

ACKNOWLEDGMENT

The author would like most sincerely to thank John R. Shepanski for many helpful discussions.

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