Is there a real time ordering behind the nonlocal correlations?

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October 20, 2001

Abstract: It is argued that recent experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations: In Bell’s world there is no “before” and “after”.

PACS numbers : 03.65.Bz, 03.30.+p, 03.67.Hk, 42.79.J

Quantum Mechanics predicts correlated outcomes in space-like separated regions for experiments using two-particle entangled states. But two events cannot be correlated if each of them takes place quite at random: “Correlations cry out for explanation”, either the events are pre-determined by some kind of hidden variables, or directly connected through some kind of influence at a distance.

If all influences in nature stick to time and never pace faster than light, the quantum correlations in space-like separated regions imply particles carrying hidden variables, which determine the particle’s behaviour. Apparently this was the way Einstein thought, and concluded that the quantum mechanical description of the physical reality cannot be considered complete. However Bell showed that if one only admits relativistic local causality (causal links with v ≤ c), the correlations occurring in two-particle experiments should fulfill clear locality conditions (“Bell’s inequalities”). Bell experiments conducted in the past two decades, in spite of their loopholes, suggest a violation of local causality: statistical correlations are found in space-like separated detections; violation of Bell’s inequalities ensure that these correlations are not pre-determined by local hidden variables. Nature seems to behave nonlocally, and Quantum Mechanics predicts well the observed distributions.

If the correlations are not pre-determined, then there are influences connecting directly two space-like separated events, even though we cannot use such “Bell influences” for faster-than-light communication. Suppose one of the measurements produces the value $\rho$ ($\rho \in \{+,-\}$), and the other the value $\sigma$ ($\sigma \in \{+,-\}$). Quantum Mechanics predicts a probability $Pr(\rho,\sigma)$ of getting the outcome $(\rho,\sigma)$, which is independent of any ordering of the events. Nevertheless this does not mean that Quantum Mechanics is incompatible with the whole idea of ordering. Effectively, one can consider that the value $\sigma$ depends on the value $\rho$ (what is not the same as saying that $\sigma$ is caused by $\rho$), and the correlations are worked out using the conditional probability:

$$Pr(\sigma|\rho) = \frac{Pr(\rho,\sigma)}{\sum_{\rho} Pr(\rho,\sigma)}$$

where $Pr(\sigma|\rho)$ is the probability that one of the particles produces the value $\sigma$ provided the other produces the value $\rho$, and $Pr(\rho,\sigma)$ is the quantum mechanical joint probability of getting the outcome $(\rho,\sigma)$.

But one can, alternatively, consider that $\rho$ depends on $\sigma$ and the correlations are worked out using the conditional probability:

$$Pr(\rho|\sigma) = \frac{Pr(\rho,\sigma)}{\sum_{\sigma} Pr(\rho,\sigma)}$$

In spite of the different orderings the equations (1) and (2) bear the same joint probability of getting the outcome $(\rho,\sigma)$, i.e., the quantity $Pr(\rho,\sigma)$ predicted by Quantum Mechanics, which is ordering independent. To produce the correlations, nature can (arbitrarily) choose between the ordering assumed in (1) and that in (2) but its choice has no observable consequence at all, and it is not possible, even in principle, to distinguish which measurement is the independent and which the dependent one. So what Quantum Mechanics actually implies is that the order the nonlocal correlations reveal does not correspond to any real time ordering and, consequently, is not tied to any experimentally distinguishable frame. Suppose a physicist could act nonlocally and would like to bring about Bell-correlations: he should choose one event as first, assign it a value at random, and then assign a value to the other event depending on the value assigned to the first. Quantum Mechanics actually means that in nature this ordering activity comes about without flow of time.

Of course, in case of experiments with time-like separated measurements one has to accept that the measurement occurring later in time takes account of that occurring before: indeed in this situation one could even arrange that the outcome in side 1 of the setup determines classically (through light signals) the phase in side 2 and, thereby, the outcome in side 2.

The time-independence of Quantum Mechanics is probably its most astonishing feature. Indeed we use to explain correlations in the physical world assuming that
a “temporally” earlier event influences a “temporally” later event. As long as one believed (following Einstein) that there are no space-like influences, the fundamental temporal notion could not be other than proper time along a time-like trajectory. But since Bell experiments did reveal us a world consisting in nonlocal influences, the “reasonable” position in the very spirit of the relativity of time is to assume that these influences can be described using several simultaneity lines to distinguish between “before” and “after”. Therefore, also taking nonlocality for granted, the decisive question remains: is there an experimentally distinguishable time ordering behind the nonlocal correlations?

The first attempt to cast nonlocality into a temporal scheme has been Bohm’s theory [9]. It uses a unique preferred frame or absolute time, in which one event is caused by some earlier event by means of instantaneous action at a distance. This description makes the same predictions as Quantum Mechanics, and the assumed instantaneous influences cannot be used for superluminal communication. The assumption of one preferred frame has been invoked recently as the most natural way to incorporate quantum nonlocality [10]. Nevertheless, if one tries to cast nonlocal causality into only one preferred frame it is not more reasonable to connect a “cause” event to an “effect” event in that frame rather than in some other frame. Effectively a single preferred frame (“quantum ether”) is “experimentally indistinguishable” [10]: The predictions would remain the same if one assumes that the preferred frame is a virtual entity changing from experiment to experiment. One is tempted to think that Bohm introduces absolute time just because he wishes to justify a causal description, but in the end, an untraceable “quantum ether” is essentially the same as deciding arbitrarily which event depends on which one. What is more, in the particular case, possible in principle, of both measurements taking place at exactly the same time in the preferred frame, the only way of establishing which event depends on which is by arbitrary decision. Actually Bohmian Mechanics and any theory using only one preferred frame, can be considered a causal description but not a real temporal one.

Work in recent years proposed to imbend nonlocality in a real relativistic time ordering by using several relevant frames. The main motivation of such a proposal is to create an experimental test allowing us to decide whether nonlocal influences can be measured by means of several real clocks. The result is a nonlocal description called Multisimultaneity or Relativistic Nonlocality [10, 11]. Aiming an explanation in terms of several real clocks, it is natural to assume that these clocks are somewhat related to the frames involved in the experimental setup. More specifically these frames are supposed to be those of the devices in which the choice of the outcome value occurs, and the monitored beam-splitters are supposed to be these “choice-devices” [12]. The basic assumption of Multisimultaneity is that the decision about the output port by which a photon leaves a beam-splitter takes account of all the local and nonlocal information available within the inertial frame of this choice-device, at the instant the particle strikes it; we stress that this frame is unambiguously defined by the velocity corresponding to the Doppler-shift of the reflected photons [11]. Within each choice-device’s frame the causal links always follow a well defined chronology, one event never depending on some future event.

In the conventional Bell experiments both beam-splitters are standing still in the laboratory frame. In this frame one of the choices (say ρ) takes place always before the other (σ), and the particle arriving later takes account of the decision of that arriving first, just as indicated in equation (1). Therefore, Multisimultaneity bears the same predictions as Quantum Mechanics. In this sense, Multisimultaneity and Bohm’s theory provide basically the same description for experiments with all choice-devices at rest, i.e. a causal explanation in which the ordering of the events fits with the time ordering in the laboratory frame.

Consider now experiments in which the choice-devices are in motion in such a way that each of them, in its own reference frame, is first to select the output of the photons (before-before timing). Then, each particle’s choice will become independent of the other’s, and according to Multisimultaneity the nonlocal correlations should disappear. By contrast Quantum Mechanics requires that the particles stay nonlocal correlated independently of any timing, even in such a before-before situation [11]. This means that before-before experiments are capable of acting as standard of time-ordered nonlocality: if Quantum Mechanics prevails, nonlocality cannot be imbedded in a relativistic chronology; if Quantum Mechanics fails, there is a time ordering behind the nonlocal correlations, and proper time along a time-like trajectory is not the only temporal notion [12].

In summary, Multisimultaneity proposes feasible experiments using moving choice-devices, which are of interest in the general context of physical situations involving several observers in relative motion [11]. Acousto-optic modulators have made it possible to perform such experiments [11]. The results recently obtained with before-after, before-before, and after-before timings uphold the predictions of Quantum Mechanics [12]. This means that in before-before experiments the correlations are caused regardless of any relativistic chronology: entangled photons run afoot of the relativity of time.

The influences allowing us to phone between two separated regions follow time-like trajectories (Fig. 1), and can consistently be described in terms of “before” and “after” by means of real clocks; Einstein’s world contains only such local causal links. The influences bringing about nonlocal correlations cannot be described in terms of “before” and “after” by means of any set of real clocks. Bell’s world consists in such nonlocal influences. The notion of time makes sense only in Einstein’s world,
i.e. along time-like trajectories.

Taken for granted the impossibility of imbedding non-locality in a relativistic chronology, we would like to finish our analysis by discussing the possibility of imbedding it in a non-relativistic temporal scheme that uses influences propagating at finite velocity $V > c$. Such a theory has been proposed by Eberhard. The value of the new constant $V$ is not given, but possible experiments are described, which would allow us to establish it providing they prove standard Quantum Mechanics wrong. Since the preferred frame is in principle experimentally distinguishable, it would define a real universal clock and, therefore, the assumed causality is a temporal one. However, the experiments proposed would not be capable of discarding the preferred-frame description: upholding of the quantum mechanical predictions would simply establish a lower bound for the speed $V$ of the superluminal influences causing the correlations. As Eberhard himself shows, the influences propagating at a finite speed $V > c$ could be used for superluminal communication. Although such signaling contradicts in every sense the convictions of what is feasible in physics after Michelson-Morley and related experiments, it doesn’t bear causal loops while only one single frame is assumed. Thus, the belief in a real preferred frame, if it is serious, should lead to real experiments aiming to demonstrate superluminal signaling. But more than signaling, we fear it is the fact that the theory cannot be falsified when tested against Quantum Mechanics that prevents physicists from performing the proposed experiments.

In conclusion, Multisimultaneity was the product of two things: the fact that nonlocal correlations evidence an ordering activity (they cannot just result by random choice), and the bias that such an ordering is always tied to a corresponding distinguishable temporal sequence. Experiments with moving beam-splitters indicate that the nonlocal correlations are brought about without relation to any real chronology: we have to give up the bias and accept time-independent Bell influences. Bell showed that Einstein’s reality is not the whole physical reality, and discovered us a world without distances. The experimental results we have discussed suggest that in Bell’s world things get along without any real time either.

I would like to thank Nicolas Gisin, Valerio Scarani, André Stefanov, and Hugo Zbinden for very stimulating discussions, and the Odier Foundation of Psycho-physics and the Léman Foundation for support.

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