Entanglement and Time

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It is argued that recent experiments testing Multisimultaneity prove that quantum entanglement occurs without the flow of time. Bohmian mechanics cannot be considered a real temporal description.

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I. INTRODUCTION

Quantum Mechanics predicts correlated outcomes in space-like separated regions for experiments using two-particle entangled states [1]. Suppose one of the measurements produces the value \( \rho \) (\( \rho \in \{+, -\} \)), and the other the value \( \sigma \) (\( \sigma \in \{+, -\} \)). According to Quantum Mechanics the probability \( \text{Pr}(\rho, \sigma) \) of getting the joint outcome \((\rho, \sigma)\) depends on the choice of the phase parameters characterizing the paths or channels uniting the source and the detectors; depending on the value of the phases, the quantity \( \text{Pr}(\rho, \rho) \) oscillates between the situation of perfect correlation \( \text{Pr}(\rho, \rho) = 1 \), and that of perfect anticorrelation \( \text{Pr}(\rho, \rho) = 0 \). Moreover \( \text{Pr}(\rho, \sigma) \) is completely independent of any time ordering of the events, i.e. in the calculation of \( \text{Pr}(\rho, \sigma) \) the quantum formalism does not bother about whether the outcome \( \sigma \) occurs before \( \rho \), and \( \rho \) depends on \( \sigma \), or conversely.

In this article we introduce the conditional probability \( \text{Pr}(\sigma | \rho) \) as the probability that one of the particles produces the value \( \sigma \) provided the other produces the value \( \rho \), and establish a correspondence between the different meanings one can attribute to this quantity and the different views about quantum entanglement. We argue that recent experiments demonstrate that the dependence expressed by \( \text{Pr}(\sigma | \rho) \) actually exists but is in principle unobservable and does not correspond to any real time ordering.

Indeed, in this situation, from any point of view, the after event \( \sigma \) does not exist when the before one \( \rho \) takes place. Moreover one could even arrange that the outcome \( \rho \) in side 1 of the setup determines classically (through light signals) the phase in side 2 and, thereby, the outcome \( \sigma \) in side 2. Experiments with time-like separated measurements show that the quantum correlations are compatible with the idea of ordered events, and even with time-ordered ones. In such experiments the correlations reveal the dependence of the later outcome on the first one, and since the events lie time-like separated this dependence can be considered a time-ordered causal link.

Consider now the case of space-like measurements. Here there is no compulsory ordering, and in principle two different descriptions are possible:

One can consider that \( \rho \) depends on \( \sigma \) and describe things according to the following equation:

\[
\text{Pr}(\rho, \sigma) = \text{Pr}(\sigma | \rho) \sum_{\rho} \text{Pr}(\rho, \sigma) \quad (1)
\]

where the conditional probability \( \text{Pr}(\sigma | \rho) \) expresses the dependence of the outcome \( \sigma \) on \( \rho \).

Or one can alternatively consider that \( \rho \) depends on \( \sigma \) and the correlations are worked out according to the following equation:

\[
\text{Pr}(\rho, \sigma) = \text{Pr}(\rho | \sigma) \sum_{\sigma} \text{Pr}(\rho, \sigma) \quad (2)
\]

where the conditional probability \( \text{Pr}(\rho | \sigma) \) expresses the dependence of the outcome \( \rho \) on \( \sigma \).

One can hardly deny that the very fact of the correlations reveals a dependence actually existing in the world: “Correlations cry out for explanation” [1], two events cannot be correlated if each of them takes place quite at random. Therefore it is astonishing that Quantum Mechanics only speaks about joint probabilities, and says nothing about conditional probabilities expressing the dependence between the outcomes. This silence protects two deep secrets.
The first one is that of Nonlocality, which John Bell unveiled. Quantum mechanics implies that the term $Pr(\sigma|\rho)$ (or $Pr(\rho|\sigma)$) corresponds to a faster than light link between outcomes. Nonlocality has been tested and did prevail against Einstein local realism (see section III below).

The second secret is Nontemporality, unveiled by recent research. The dependence expressed by the term $Pr(\sigma|\rho)$ (or $Pr(\rho|\sigma)$), actual though it is, it doesn’t correspond to any real temporal ordering, it doesn’t have any observable counterpart. The correlations arise without the flow of time. Nontemporality has been tested and did prevail against Multisimultaneity (see section V below).

III. TESTING NONLOCALITY VS EINSTEIN’S LOCAL REALISM

According to the local view of Relativity one has to exclude any link faster than light and, therefore, any direct connection between space-like separated regions. This means that the dependence expressed by $Pr(\sigma|\rho)$ or $Pr(\rho|\sigma)$ does not arise from a direct link between the two measurements, but originate from some common cause in the absolute past of both measurements. Apparently this was the way Einstein thought, and concluded that the quantum mechanical description of the physical reality cannot be considered complete.

However John Bell showed that if one only admits relativistic local causality (causal links with $v \leq c$), the correlations occurring in two-particle experiments should fulfill clear locality conditions (“Bell’s inequalities”), which by contrast are violated by Quantum Mechanics (Bell’s theorem). 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 some common cause in the past. Nature seems to behave nonlocally, and Quantum Mechanics predicts well the observed distributions.

Even if the quantum nonlocality violates Einstein’s view that nothing in nature goes faster than light, it does not lead to any conflict with Relativity on the level of the observations. Effectively, the quantum mechanical formalism ensures that the unobservable “Bell’s connections” cannot be used to phone faster-than-light.

IV. BOHM’S THEORY

If the correlations are not pre-determined, then there must be some direct dependence or connection between two space-like separated events. But what kind of causality does such a direct dependence involve?

Bohm’s theory was the first attempt to cast nonlocality into a time-ordered causal scheme. It gives up the relativity of time and 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. The value occurring later in this preferred frame, say $\sigma$ depends on the value $\rho$ occurring before. In this sense Bohm’s action at a distance refers to a causal link though not a Lorentz-invariant one. The description makes always the same predictions as Quantum Mechanics. At the observable level no conflict with relativity arises.

However, 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”. 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 can be considered a causal description but not a real temporal one, and to date it has not lead to experiments capable of distinguishing it from Quantum Mechanics. Regarding the meaning of the dependence $Pr(\sigma|\rho)$, in the end Bohmian Mechanics shares the same view as Quantum Mechanics: The dependence actually exists but it is essentially unobservable; the ordering expressed in $Pr(\sigma|\rho)$ does not correspond to any real time ordering.

V. TESTING NONTEMPORALITY VS MULTISIMULTANEITY

As long as one believed (according to 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 a world consisting in nonlocal connected events, the “reasonable” position in the very spirit of relativity is to assume time-ordered causality, and describe the nonlocal links using lines of simultaneity to distinguish between “before” and “after”.

Indeed, such a description is very well possible in conventional Bell experiments, in which all apparatuses are standing still in a laboratory frame. Since the emission time of the photons is not exactly the same, and the fibers guiding the photons from the source to the measuring devices do not have exactly the same length, according to the clock defined by the laboratory’s inertial frame, one of the measurements always takes place before the other, and the particle arriving later can be considered to take
account of the outcome of the one arriving before. In fact, this is the way Bell tried to explain things, and, in doing so (i.e. assuming that \( Pr(\sigma|\rho) \) reflects the the time-ordering in the laboratory frame) he came to discover quantum nonlocality \[1\]. Orderings with one measurement before and the other after in time are referred to as before-after or after-before timings. In experiments with all measuring devices at rest, it is possible to explain quantum correlations through time-ordered (nonlocal) causality.

But what about experiments with moving apparatuses in which several relevant frames are involved? In this case, different clocks watch the arrival times, and what is “after” according to the laboratory clock may become “before” according to one moving clock. Then, it is possible to define other time orderings: If each measuring device in its own reference frame is the first to select the output of photons, we have before-before timing. If each measuring device in its own reference frame selects the photon output after the other, we have after-after timing. Is it also possible to give a time-ordered causal explanation for relativistic experiments using apparatuses in motion?

Recently, an alternative nonlocal description called Multisimultaneity has been proposed, which extends the time-ordered description to experiments with before-before and after-after timings \[5, 6, 7\]. This description imbeds nonlocality in a real relativistic time ordering by using several relevant frames. The main motivation of such a proposal is to create an experiment allowing us to decide whether nonlocal influences can be measured by means of several real clocks.

Multisimultaneity assumes basically Bohm’s idea of time-ordered nonlocal causality but uses real and well defined inertial frames to describe the causal links: the inertial frames of the measuring devices. The basic assumption of Multisimultaneity is that the decision about the output port by which a photon leaves a choice-device 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. The dependence expressed by \( Pr(\sigma|\rho) \) is tied to an experimentally well defined inertial frame and corresponds to a real time ordering. Within each choice-device’s frame the causal links always follow a well defined chronology, one event never depending on some future event.

As said, in the conventional Bell experiments there is only one relevant frame, and in it one of the choices, say \( \rho \), takes place always before the other \( \sigma \), 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 experiments with all devices at rest it is possible to give 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 \[3\]. This means that before-before experiments are capable of acting as standard of time-ordered nonlocality (much as Bell’s experiments act as standard of locality): if timing-independent 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 \[12\].

As a matter of fact, the conventional Bell experiments did not test in any way whether or not entanglement depends on the timing of the measurements in relativistic setups. Therefore, also taking nonlocality for granted, it was necessary to make experiments with moving measuring devices.

This means that if one invokes a description assuming the quantum collapse one has to put the detectors in motion, and if one invokes a description without collapse (in the line of Bohm’s theory) the monitored beam splitters. We stress that in case of the beam splitters this frame is unambiguously defined by the velocity corresponding to the Doppler-shift of the reflected photons \[9\].

Multisimultaneity proposes feasible experiments using moving choice-devices \[5, 6, 7\], which are of interest in the general context of physical situations involving several observers in relative motion \[13\], specially to the aim of testing the timing-independence of the quantum probabilities. All four possible relativistic timings have been experimentally tested. In February 2000 experiments using moving detectors showed results in agreement with Quantum Mechanics \[14\], i.e. no disappearance of the correlations was observed with before-before and after-after timing. More recently, acousto-optic modulators have made it possible to perform experiments with moving beam-splitters \[9\]. The results obtained in June 2001 upheld the predictions of Quantum Mechanics too \[10\].

VI. OTHER TEMPORAL SCHEMES

We discuss now two other ways of imbedding entanglement in a temporal scheme, which have strong implications for the understanding of causality and involve peculiar experimental conditions.

Ph. Eberhard’s theory uses influences propagating at finite velocity \( V > c \). Such a theory has been proposed by \[14\]. 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. Thus, the belief in a real preferred frame, if it is serious, should lead to real experiments aiming to demonstrate superluminal signaling. But we fear the fact that the theory cannot be falsified when tested against Quantum Mechanics is preventing physicists from performing the proposed experiments.

O. Costa de Beauregard sticks to Einstein’s postulate that any causal link has a Lorentz invariant counterpart in the formalism, and proposes to explain entanglement by means of influences propagating along the light-cone but backwards in time (retrocausation). The measurement of one of the particles does not influence directly the other particle but the source through backwards causation.

In reality backwards causation is the strongest form of the bias that causality is always bond to the flow of time (one could also say the bias that all causal links have to be essentially Lorentz invariant): If one cannot bind causality to the time flowing forwards, one binds it to the time flowing backwards! This view seems to bear a big problem in situations in which the two measurements lie time-like separated, for instance the measurement of photon 2 lies in the future light cone of the measurement of photon 1. Indeed, in this case backwards causation means that an event occurring at time $T$ (the measurement of photon 1) is determined by another event (the measurement of photon 2), which at time $T$ has no existence at all in any possible inertial frame (of the source or other).

As far as such a view does not imply observable effects there is no problem in maintaining it: it is merely another way to say the same as Quantum Mechanics, as it is the case also for Bohm’s theory. Nevertheless Costa de Beauregard pretends that backwards causation should have observable implications in experiments involving psi-subjects enjoying capacities as telepathy. In experiments with entangled particles, such psi-subjects are supposed to be capable of influencing on purpose the probability to get a particular outcome, say $+$, on one side of the setup, and because entanglement they would also change faster than light the corresponding probability on the other side. This would imply the possibility of signaling faster than light and, therefore, of changing the past. As it seems, there is work in progress to test Costa de Beauregard’s prediction. Additionally to the difficulty of establishing which subjects can be considered to posses psi-capacities, the question is whether the corresponding experiments will be acknowledged as valuable tests beyond the psi-community.

VII. CONCLUSION

The results of experiments with moving measuring devices mean that the quantum correlations are caused regardless of any relativistic chronology: entangled photons run afoot of the relativity of time, Einstein’s frames have no effect on “spooky action”, even though we cannot use this fact to establish an absolute time.

So what Quantum Mechanics actually implies is that in case of space-like separated measurements the dependence the correlations reveal does not correspond to any real time ordering and, consequently, is not tied to any experimentally distinguishable frame. In spite of the different orderings the equations $\rho$ and $\sigma$ bear the same joint probability of getting the outcome $(\rho, \sigma)$, i.e., the measurable quantity $Pr(\rho, \sigma)$ predicted by Quantum Mechanics, which is independent of any ordering and timing. To produce the correlations, nature can choose between the ordering assumed in $\rho$ and that in $\sigma$ 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. Any observer who would record the temporal sequence of the outcomes in his own frame, and assume that the outcome later in time depends on the earlier one according to one of the rules ($\rho$ or $\sigma$), would make the same predictions as Quantum Mechanics.

The term $Pr(\rho, \sigma)$ expressing the measurable joint probability of getting a given outcome is perfectly Lorentz-invariant. As for the quantities $Pr(\sigma|\rho)$ and $Pr(\rho|\sigma)$ expressing the dependence between the events they are certainly not Lorentz invariant but don’t have any measurable counterpart. Quantum entanglement implies causal links which are not Lorentz-invariant. Nevertheless such causal links do not imply any observable violation of Lorentz invariance at all.

The influences allowing us to phone between two separated regions follow time-like trajectories, 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 entanglement bringing about nonlocal correlations is insensible to space and time, and cannot be described in terms of “before” and “after” by means of any set of real clocks. The notion of time makes sense only in Einstein’s world, i.e. along time-like trajectories. Suppose a physicist could act non-locally and would like to bring about Bell-correlations; she or he would first choose one event assigning randomly a value (either $+$ or $-$) to it, and subsequently would assign a value depending upon the first, to the second event. Suppose these operations occur without the flow of time; as Quantum Mechanics seems to mean, and the experimental results confirm, this is the way things happen in nature.

In conclusion the experiments testing quantum entanglement rule out the belief that physical causality necessarily relies on observable signals. Quantum entanglement supports the idea that the world is deeper than
the visible, and reveals a domain of existence, which cannot be described with the notions of space and time. In the nonlocal quantum realm there is dependence without time, things are going on but the time doesn’t seem to pass here.

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