Does entanglement depend on the timing of the impacts at the beam-splitters?

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A new nonlocality experiment with moving beam-splitters is proposed. The experiment is analysed according to conventional quantum mechanics, and to an alternative nonlocal description in which superposition depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters.

Keywords: relativistic nonlocality experiment, timing-dependent entanglement.

1 Introduction

Entanglement is Schrödinger’s name for superposition in a multi-particle system. In particular he called entangled states two-particle states that cannot be factored into products of two single-particle states in any representation. Multi-particle superposition is considered to be the characteristic trait of quantum mechanics [1]. If one cannot distinguish (even in principle) between different paths from source to detector, the amplitudes for these alternative paths add coherently, and multi-particle correlations appear. If it is possible in principle to distinguish, correlations vanish. Work by John Bell [2], by Daniel M. Greenberger, Michel A. Horne, and Anton Zeilinger [3], and by Lucien Hardy [4] pointed out that local-realistic theories cannot account for the superposition principle. If one accepts that relativity experiments like Michelson-Morley only imply a practical impossibility for man to communicate faster than light, no contradiction between these experiments and quantum mechanics arises.

However, the heart of relativity is the conclusion that there is no absolute spacetime, no "aether". Simultaneity depends on the observer’s state of movement, the order of succession of two space-like separated events may change if one changes the inertial frame. Relativity of space-time seems to be at odds with the quantum mechanical assumption that superposition depends exclusively on indistinguishability [5, 6, 7], and not on the times at which the values are measured, in any inertial frame whatsoever. Consider for instance the orthodox quantum mechanical description of the perfect EPR correlations in two-particle experiments with entangled polarized photons: according to the superposition principle, the spin operator related to a measuring apparatus with two parallel oriented polarizing beam-splitters has two eigenvectors $|+1, +1\rangle$ and $|-1, -1\rangle$, representing two orthogonal quantum eigenstates; the measurement causes the entangled state to jump into either the state $|+1, +1\rangle$ or the state $|-1, -1\rangle$ instantaneously, where the first state means that both photons are detected in the detectors monitoring the transmitted output ports, and the second one that both photons are detected in the detectors monitoring the reflected output ports. Consequently, the measurement produces events which are simul-
between local correlations necessarily express a link existing values. Therefore, the appearance of perfect non-or, what is the same, the measurement creates the postulate, only after a specific measurement has been made can we attribute a definite space-time or quantum aether, the superposition principle seems to contradict somewhat another self. No matter if one accepts the relativity of spacetime and assume an absolute order of succesion or "quantum aether" \[9\]. Besides this conflict between relativity and quantum mechanics, we would like to highlight another problem more intrinsic to quantum mechanics itself. No matter if one accepts the relativity of space-time or quantum aether, the superposition principle seems to contradict somewhat another main postulate of orthodox quantum mechanics, namely "no values prior to the measurement". According to this postulate, only after a specific measurement has been made can we attribute a definite physical property to a quantum system: there are no pre-existing values prior to the measurement, or, what is the same, the measurement creates the values. Therefore, the appearance of perfect non-local correlations necessarily express a link existing between real measured values, and one is led to assume that the measurement at one of the regions produces either a value +1 or −1 after taking into account the value that has actually been measured in the other region. This means that there is an order of succession, and thus the perfect correlations should disappear if the measurement in region 1 occurs, in the inertial frame of the analysing device in this region, before the measurement in region 2, and the measurement in region 2 occurs, in the inertial frame of the analysing device in this region, before the measurement in region 1. But even if one assumes a universal order of succesion and rejects the possibility two perform two "before" measurements, one has to admit the possibility of simultaneous measurements. For such a case it is absurd to assume together that photon 1 impacting at beam-splitter 1 chooses the output port taking account of the choice photon 2 has really made at beam-splitter 2, and photon 2 chooses taking account of the choice photon 1 has really made. Therefore, in the case of simultaneous measurements in absolut space-time, the perfect correlations should also disappear. The superposition principle looks, therefore, to be at odds not only with relativity, but also with the postulate of "no values prior to the measurement".

The purpose of this letter is to stress that quantum mechanics (QM in what follows) is a particular view of the relationship existing between superposition and indistinguishability, but that other views are possible. QM considers indistinguishability to be a sufficient condition for superposition. However, at the present time exclusively non-relativistic experiments without moving devices have been done. Strictly speaking, such experiments support only the view that indistinguishability is a necessary condition for superposition. On this line of thinking we present in the following the basic features of an alternative nonlocal description which assumes that superposition does not depend exclusively on indistinguishability but also on the timing of the impacts at the beam-splitters. Furthermore we propose a relativistic experiment that may allow us to decide between this alternative view and QM.

### 2 Definitions and Principles of the Alternative Description (AD)

Consider the experiment with polarized photons sketched in Fig.1. Two classes of photon pairs, \((H_1, H_2)\) and \((V_1, V_2)\), are prepared through down-conversion in the "Bell state":

\[
|\phi\rangle = \frac{1}{\sqrt{2}}(|H_1, H_2\rangle - |V_1, V_2\rangle)
\]  

(1)

where \(H\) and \(V\) indicate horizontal and vertical polarization, respectively. The polarizing beam-splitters \(BS_1\) and \(BS_2\) are vertical oriented, and preceded by half wave plates, which rotate the polarization of the photons by angles \(\alpha, \beta\). Suppose each beam-splitter can move fast, and change from one inertial frame to another.

The proposed AD is based on the following definitions and principles:

If it is in principle impossible to know to which input sub-ensemble of \(BS_i, i \in \{1, 2\}\), a particle belongs by detecting it after leaving \(BS_i\), then the impact at \(BS_i\) is referred to as originating indistinguishability or uncertainty, and labeled \(u_i\). If it is in principle possible to know to which input sub-ensemble of \(BS_i\) a particle belongs by detecting it
after leaving $BS_i$, then the impact at $BS_i$ is referred to as making possible distinguishability, and labeled $d_i$.

At the time $T_i$ at which a particle $i$ arrives at $BS_i$, we consider whether in the inertial frame of this beam-splitter, particle $j$ ($j \in \{1, 2\}, j \neq i$) has already made a $u_j$ impact or not, and introduce the following definitions:

**Definition 1:** the impact of particle $i$ in $BS_i$ is a before event $b_i$ if:

1. it is a $u_i$, and
2. either the impact of particle $j$ at $BS_j$ is a $d_j$ one; or ($T_i < T_j$), the subscript $i$ after the parenthesis meaning that all times referred to are measured in the rest frame of $BS_i$.

**Definition 2:** the impact of particle $i$ in $BS_i$ is a non-before event $a_i$ if:

1. it is a $u_i$, and
2. the impact of particle $j$ at $BS_j$ is a $u_j$ one,
3. ($T_i \geq T_j$).

We can now state the two principles of AD:

**Principle I:** if the impact of a photon $i$ at $BS_i$ is a $b_i$ impact, then photon $i$ produces values taking into account only local information, i.e., it is not influenced by the parameters photon $j$ meets at the other arm of the setup.

**Principle II:** if the impact of a photon $i$ at $BS_i$ is a $a_i$ impact, then photon $i$ takes account of photon $j$ in such a way that the values photon $i$ actually produces, and the values photon $j$ produces in a $b_j$ impact are correlated according to the superposition principle.

Assuming **Principle I** and **Principle II** we implicitly discard the hypothesis that the values produced by a particle, say photon 1, depend on the state of movement of the detectors $D_1$. Effective, the experimental data suggest that the outcome distribution does not depend on the distances at which the detectors are placed with respect to the beam splitters [10]. This is also in accord with the quantum mechanical formalism. It is reasonable, therefore, to assume that the value produced by photon 1, if it is detected after leaving splitter $BS_1$ and there is no other splitter between $BS_1$ and the detector, is determined at the time the photon leaves the splitter (certainly, as far as the photon is not detected, it is always possible for the physicist to let the photon pass to a further interferometer and to oblige it to change the outcome distribution). We **discard** also the hypothesis that the values produced by photon 1 depend on the time at which photon 2 impacts at a detector $D_2$, because there is experimental evidence against it [11].

3 Consequences

We begin by introducing some notation: an experiment $e$ will be labeled by indicating the kind of impact that each particle undergoes, i.e., $e = (a_1, b_2)$. Expressions like $P(e_{\sigma, \omega})$, $\sigma, \omega \in \{+,-\}$, denote the probabilities to obtain the indicated detection values in experiment $e$ (i.e., photon 1 is detected in $D_1(\sigma)$, photon 2 in $D_2(\omega)$). In a similar way, we write $P_{QM}(e_{\sigma, \omega})$ for the probabilities predicted by standard QM for experiment $e$ (note that in this case the impacts can only be $u_i$ or $d_i$, since QM doesn’t consider differences in timing).

**Principle II** implies that

$$P((a_1, b_2)_{\sigma, \omega}) = P((b_1, a_2)_{\sigma, \omega}) = P_{QM}((u_1, u_2)_{\sigma, \omega}).$$

(2)

In all interference experiments performed till now both splitters were at rest, and one of the impacts did happen always before the other. Then, according to Equation (2), AD reduces to QM for all experiments already done.

On the other side, it follows from **Principle I** that

$$P((b_1, b_2)_{\sigma, \omega}) = P_{QM}((d_1, d_2)_{\sigma, \omega}) = P_{QM}((u_1, d_2)_{\sigma, \omega}) = P_{QM}((d_1, u_2)_{\sigma, \omega}).$$

(3)

Experiments in which both impacts are non-before events, or in which the photons impact successively in several beam-splitters, as well as the generalization to n-particle experiments are discussed in other articles.

Suppose now that the state of movement of the beam-splitters implies the following situation: The impact at $BS_1$, in the inertial frame of $BS_1$, occurs before the impact at $BS_2$, and the impact at $BS_2$ in the inertial frame of $BS_2$, occurs before the impact at $BS_1$. The diagram in Fig.2 corresponds to such a gedanken Experiment: It is assumed that the photons are channeled from the source to the beam-splitters by means of optical fibers, and that the optical path $S-BS_2$ traveled by photon 2, is a
4 Possibility of a real experiment

What about the possibility of doing a real experiment allowing us to distinguish between the two descriptions? The condition, guaranteeing that the impact of photon 2 at BS$_2$ occurs in the inertial frame of BS$_2$ before the impact of photon 1 at BS$_1$, can be easily derived from the diagram of Fig.2:

$$\tan \theta = \frac{V}{c} = \frac{c(\tau + \delta t)_{\text{max}}}{L}$$  \hspace{1cm} (6)

where $V$ is the velocity of BS$_2$, $c$ is the speed of light, $L = L_1 + L_2$ and $(\tau + \delta t)_{\text{max}}$ is the maximal delay between the two impacts. For photon produced by down-conversion, $\tau \ll \delta t$, so equation (6) imposes the following condition to the value of $\delta t$:

$$\delta t < \frac{V L}{c^2}.$$  \hspace{1cm} (7)

Velocities of about 100 m/sec (360 km/h) can be reached by setting BS$_2$ on a fast moving wheeler (note that, according to AD, detectors don’t need to move). Bell-experiments with over 4 km of optical fiber have been done [13]: an experiment with such a value for the distance $L$ between the beam-splitters would allow us an upper limit for parameter $\delta t$ of 4.4 ps. A quantum channel of 24 km, has already been achieved [13]: an experiment with such a value of $L$ would allow us an upper limit for $\delta t$ of 26.4 ps. The ongoing effort to achieve quantum cryptography over long distances, may make possible values of $L$ greater than 100 km in near future, which would mean that $\delta t$ could reach values of 111 ps. The feasibility of the relativistic experiment depends, therefore, basically on the capability to ensure a significant number of impacts respecting such limits for $\delta t$. Work to clarify whether the control of the setup’s geometry can be implemented to this extent with reasonable effort is in progress.

5 Conclusion

In conclusion, the nonlocality of quantum mechanics is so important and counterintuitive that as many experiments as possible should be performed to get deeper insight in its nature. If the proposed relativistic experiment with moving beam-splitters can be carried out and the results uphold the predictions of the conventional superposition principle, then it will be hard to maintain the belief of the "pacific coexistence" between relativity and quantum mechanics. Then models giving up relativity of space-time like Bohm’s causal model [4], should be explored more in depth. On the contrary, if
the results of the experiment with moving beam-splitters prove to be in conflict with quantum mechanics, the road to a new description of physical reality would be opened. This description would base on two main assumptions: (1) there are in nature faster than-light-influences which cannot be used by man for superluminal signaling, and (2) superposition depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters. Such a description would be perfectly coherent with both, quantum nonlocality and space-time relativity. The realization of experiments allowing us to investigate time orderings different of the conventional ones appears promising in any case [4].

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