Can Quantum Nonlocality Be the Consequence of Faster-Than-Light Interactions?

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Abstract

It has been advocated by Bell and Bohm that the Einstein-Podolsky-Rosen (EPR) correlations are mediated through faster-than-light (FTL) interactions. In a previous paper a way to avoid causal paradoxes derived from this FTL hypothesis (via the breakdown of Lorentz symmetry) has been suggested. Lorentz transformations would remain valid, but there would be no equivalence between active and passive Lorentz transformations in the case of EPR correlations. Some counterintuitive consequences of this assumption are briefly examined here.

In a previous paper [1] we investigated the idea advocated by Bell and Bohm [2] according to which EPR correlations are mediated through superluminal interactions. It has been shown that the formalism of quantum mechanics leads to the conclusion that acting on one of the photons of an entangled pair it is possible to force the other distant photon into a well-defined polarization state. Although the argument is based on time-like events, it seems reasonable to infer that such forcing does not cease to occur in the case of space-like events, since the very same correlations are observed. The consequence of assuming a finite speed for this FTL interaction [3] has been critically analyzed, showing that the conclusion that it leads to the possibility of superluminal communication is not inescapable. Finally, a way to avoid causal paradoxes derived from the FTL hypothesis was suggested via the breakdown of Lorentz symmetry. Lorentz transformations would remain valid, but there would be no equivalence between active and passive Lorentz transformations in the case of EPR correlations. I intend to examine some consequences of this idea here.

As in [1], we will consider a pair of reference frames, \( S \) and \( S' \), in the standard configuration, where \( S \) is the privileged frame and \( S' \) is the laboratory frame moving with velocity \( v < c \) along the \( x \) axis, and pairs of photons (\( \nu_1 \) and \( \nu_2 \)), that propagate in opposite directions, in the polarization-entangled state

\[
| \psi \rangle = \frac{1}{\sqrt{2}}(| a_\parallel \rangle_1 | a_\parallel \rangle_2 + | a_\perp \rangle_1 | a_\perp \rangle_2), \tag{1}
\]
where \( a_\parallel \) and \( a_\perp \) represent arbitrary mutually orthogonal directions. An interesting question is: Is it possible, being in \( S' \) and using EPR correlations, to determine \( v \)? The main difficulty is that we cannot “see,” so to speak, when the second photon is forced (due to the action on the first photon) into a well-defined polarization state. Furthermore, it is not possible to know which photon is “really” detected first [4]. I would like to examine here some curious and counter-intuitive consequences of our basic assumption according to which the FTL interaction propagates isotropically in \( S \) with a constant speed \( \bar{u} > c \), irrespective of the velocity of the source [1]. It is instructive to see how things work.

(A) In the first situation to be considered, \( \nu_1 \) and \( \nu_2 \) are emitted at instant \( t'_0 = 0 \) from the source \( S \), which is at \( x'_0 = 0 \) in \( S' \), and propagate along the \( x \) axis in opposite directions. In \( S \) they are emitted at instant \( t_0 = 0 \) from \( x_0 = 0 \). Photon \( \nu_1 \) (\( \nu_2 \)) is detected at point \( x'_1 = -l \ (x'_2 = l) \), with \( l > 0 \), at instant \( t'_1 = l/c \ (t'_2 = l/c) \) [5]. The Lorentz transformations connecting \( S \) and \( S' \) are:

\[
x' = \gamma (x - vt),
\]

\[
t' = \gamma \left( t - \frac{v}{c^2}x \right),
\]

\[
x = \gamma (x' + vt'),
\]

and

\[
t = \gamma \left( t' + \frac{v}{c^2}x' \right),
\]

where \( \gamma = 1/\sqrt{1 - v^2/c^2} \), from which we derive the expressions

\[
u'_x = \frac{u_x - v}{\gamma^2},
\]

and

\[
u_x = \frac{u'_x + v}{\gamma^2}
\]

for the velocities. Using (4) and (5) we see that in \( S \) the photons are detected at

\[
x_1 = -\gamma(1 - \frac{v}{c})l
\]

and

\[
x_2 = \gamma(1 + \frac{v}{c})l
\]

at instants

\[
t_1 = \gamma(1 - \frac{v}{c})\frac{l}{c}
\]

[5]
and
\[ t_2 = \gamma \left( 1 + \frac{v}{c} \right) \frac{l}{c}. \] (11)

Let us assume that \( u_x = \overline{u} \to \infty \) for the velocity of the FTL interaction in \( S \). Then, from (6) we obtain \( \overline{u}'_x = -c^2/v \), for the velocity of the FTL interaction in \( S' \). Photon \( \nu_1 \) is detected at \( t_1 < t_2 \) in \( S \). Whenever this takes place, \( \nu_2 \) is instantaneously forced into a well-defined polarization state (since \( \overline{u} \to \infty \) in \( S \)), having traveled the distance \( ct_1 \). Using (2) and (10) we see that in \( S' \) it has traveled the distance
\[ x_F' = \gamma (ct_1 - vt_1) = \left( \frac{c - v}{c + v} \right) l. \] (12)

Therefore, in \( S' \) photon \( \nu_2 \) “spontaneously” acquires a well-defined polarization state when it is at \( x_F' \), at instant \( t_F' = x_F'/c \) (in \( S' \) \( \nu_1 \) has not yet reached the detection point) [6]. Immediately an FTL interaction is triggered that goes from \( x_F' \) to \( x_1' \), travelling the distance
\[ x_F' + |x_1'| = \frac{2cl}{c + v} \] (13)
in the time interval given by
\[ t_1' - t_F' = \left( \frac{2v}{c + v} \right) \frac{l}{c}. \] (14)

Therefore, in \( S' \) the FTL interaction propagates in the \(-x\) direction with the speed
\[ \frac{x_F' + |x_1'|}{t_1' - t_F'} = \frac{c^2}{v}, \] (15)
as it should be, and reaches \( \nu_1 \) exactly when it is being detected.

(B) In the second situation, we consider the same experiment discussed in (A), but now we are assuming \( u_x = \overline{u} \neq \infty \), and \( v \) is chosen to have \( v\overline{u}/c^2 = 1 \), which leads, using (6), to \( \overline{u}'_x \to \infty \). (It is worth noting that \( u_x = -\overline{u} \) leads to \( \overline{u}'_x = -(\overline{u} + v)/2 \). The FTL interaction does not propagate isotropically in \( S' \).) In \( S' \), photons \( \nu_1 \) and \( \nu_2 \) are detected at the same time and are then instantly connected by the FTL interaction which propagates with infinite speed from \( \nu_1(\nu_2) \) to \( \nu_2(\nu_1) \). In \( S \), photon \( \nu_1 \) is detected first, at instant \( t_1 \) given by (10), which triggers an FTL interaction sent in the direction of \( \nu_2 \). Let us calculate the instant \( t_F \) when the interaction reaches the point at which \( \nu_2 \) will be detected. The interaction is sent at instant \( t_1 \), it then propagates to \( x_0 \) and then to \( x_2 \), given by (9). From our choice for \( v \) we get \( \overline{u} = c^2/v \), hence
\[ t_F = \gamma \left( 1 - \frac{v}{c} \right) \frac{l}{c} + \gamma \left( 1 - \frac{v}{c} \right) \frac{l}{u} + \gamma \left( 1 + \frac{v}{c} \right) \frac{l}{u} = \gamma \left( 1 + \frac{v}{c} \right) \frac{l}{c} = t_2. \] (16)
Therefore, in S the interaction reaches \( \nu_2 \) exactly when it is being detected.

Apparently, there seems to be no practical way to distinguish between situations (A) and (B) since, as previously observed, it is not possible to know which photon is really detected first, nor when the FTL interaction reaches the second photon. Actually, to determine if \( \bar{u} \neq \infty \), the ideal is that in which the detection points are equidistant from the source in the preferred frame. If photon \( \nu_1 \) (\( \nu_2 \)) is detected at point \( x'_1 = -l_1 \) \( (x'_2 = l_2) \), with \( l_1 \) \( (l_2) \rangle > 0 \), replacing \( l \) by \( l_1 \) \( (l_2) \) in (8) \((9)\) and making \( -x_1 = x_2 \) we obtain

\[
 l_1 = \left( \frac{c + v}{c - v} \right) l_2, \tag{17}
\]

as the best choice.

It is interesting to reexamine situation (B). If \( \bar{u} \) is finite and the detection points are equidistant from the source in the preferred frame, no EPR correlations are to be expected. From (17) we see that in the laboratory frame \( \nu_2 \) is detected first, which triggers an FTL interaction in the direction of \( \nu_1 \). As already emphasized, this interaction propagates with a finite speed equal to \( (\bar{u} + v)/2 \), and it is easy to verify that it cannot reach \( \nu_1 \) before it is detected. On the other hand, when \( \nu_1 \) is detected, an FTL interaction with infinite speed is sent, but it cannot reach \( \nu_2 \) since it has already been detected. Therefore, although we have two different interpretations for the same experiment, depending on the reference frame we use to describe it, they lead to the same predictions. One possible difficulty is that the FTL speed can be exceedingly large and, strictly speaking, the photons are never detected at exactly the same time. Therefore, even observing EPR correlations, it is not possible to conclude with absolute certainty that \( \bar{u} \to \infty \). On the other hand, if no EPR correlations are observed, the next step would be to change the relationship between \( l_1 \) and \( l_2 \) to make the correlations appear.

(C) In the third situation, we will consider that the detection points are along the y axis in \( S' \) \( (y'_1 = -l_1, y'_2 = l_2) \) and the source of the entangled photons is at \( y'_0 = 0 \). In the standard configuration, we have

\[
y' = y. \tag{18}
\]

Hence, using (18) and (5) we obtain

\[
 u_y = \frac{u'_y/\gamma}{1 + \frac{vu'_x}{c^2}}, \tag{19}
\]
Assuming $u'_x = \overline{u}_x = 0$, and $u'_y = \overline{u}_y$, from (7) and (19) we obtain

$$\overline{u}_x = v$$

(20)

and

$$\overline{u}_y = \overline{u}_y \left(1 - \frac{v^2}{c^2}\right)^{1/2}. $$

(21)

Since $\overline{u}_x^2 + \overline{u}_y^2 = \overline{u}^2$, from (20) and (21) we obtain

$$\overline{u} = \left[v^2 + (\overline{u}_y)^2 \left(1 - \frac{v^2}{c^2}\right)^{1/2}\right]. $$

(22)

Hence, knowing $\overline{u}_y$, the speed of the FTL interaction in $S'$ along the $y$ axis, and $v$, the speed of the laboratory frame relative to $S$, the preferred frame, it would be possible to determine $\overline{u}$, namely the speed of the FTL interaction in $S$.

\[\text{Fig.1}\]

Returning to the question posed at the beginning of this article, it seems possible, at least in principle, to determine the velocity of the moving frame $S'$ relative to the privileged frame $S$, provided that the speed $\overline{u}$ of the superluminal interaction in $S$ is finite [7]. It is possible to devise a way to try to determine $\overline{u}'$, the speed of the superluminal interaction in $S'$ (not forgetting that, contrary to what occurs in $S$, it will depend on the direction of propagation in $S'$). I believe it has become evident that this is a more complicated task than it may seem at first sight. With this in mind, we can imagine the following experiment. Let us consider a modified version of the experiment depicted in Fig.1 [A source (S) emits a pair of polarization-entangled photons ($\nu_1$ and $\nu_2$) that propagate in opposite directions and impinge respectively on two-channel polarizers (I and II). A detour is introduced to have time-like events in which $\nu_1$ is always detected before $\nu_2$.]. A second detour is introduced
between the source and polarizer I. The height of the detours can be adjusted continuously. Initially (Fig.1), the height of the left detour is zero, and the height of the right detour is chosen to have $\nu_1$ being detected before $\nu_2$ in all Lorentz frames (time-like events). We assume that in the first situation the supposed superluminal interaction propagates from left to right. We then go on increasing the height of the left detour continuously while, at the same time, we decrease the height of the right detour continuously. Continuing with this process, we will arrive at a situation in which it is now $\nu_2$ that is detected before $\nu_1$ in all Lorentz frames. In this second situation the superluminal interaction propagates from right to left. It is to be assumed that between situations one and two there must be a region (involving space-like events) in which the superluminal interaction no longer has an effect. (Interestingly, in this experiment the detectors do not need to be far from the source.) In principle, this would allow us to determine $\pi'$. Naturally, since there is no isotropy, we would have different values for $\pi'$ propagating from left to right and from right to left. In addition, rotating the experimental apparatus, we would obtain other values for $\pi'$. To see this, instead of using (2) and (3), we can use the equations below, that connect $S$ to $S'$ “for the general case where the x-axis is not in the direction of the velocity $v$” [8],

$$r' = r + \frac{1}{v^2}(\gamma - 1)(r \cdot v)v - \gamma vt$$

(23)

and

$$t' = \gamma(t - \frac{r \cdot v}{c^2})$$

(24)

which leads to

$$u' = \frac{1}{\gamma(1 - u \cdot v/c^2)} \left[ u + \frac{1}{v^2}(\gamma - 1)(u \cdot v)v - \gamma v \right].$$

(25)

From the standpoint of $S$, if $u = \overline{u}$, we obtain $\overline{u} \cdot v = \overline{uv} \cos \theta$, where $\theta$ is the angle between the direction of propagation of the superluminal interaction and the direction of propagation of $S'$. In short, no contradiction seems to arise from the breaking of equivalence between active and passive Lorentz transformations in the case of EPR correlations. We merely have to keep in mind that the “correct” explanation, so to speak, is the one based on what occurs in the privileged frame of reference. In principle, it is possible to determine $\pi$, namely the speed of the superluminal interaction in $S$, and $v$, the speed of $S'$ relative to $S$, using the equation that connects the velocities in $S'$ to the velocities in $S$:

$$u = \frac{1}{\gamma(1 + u' \cdot v/c^2)} \left[ u' + \frac{1}{v^2}(\gamma - 1)(u' \cdot v)v + \gamma v \right].$$

(26)
Since $\mathbf{u} \cdot \mathbf{u} = \mathbf{u}^2 = \text{const.} [\mathbf{u} \neq \mathbf{u}(\theta)]$, measuring $\mathbf{u}$ for n different directions we obtain n equations which, at least in principle, would allow us to determine $\mathbf{v}$. Since $\mathbf{v} \cdot \mathbf{v} = v^2$ and $\mathbf{u}' \cdot \mathbf{v} = \mathbf{u}' v \cos \theta'$, the unknowns are $v$ and $\theta'$, where $\theta'$ is the angle between the direction of propagation of the superluminal interaction, seen from $S'$, and the direction of propagation of $S'$. In the first measurement we have an unknown $\theta'$, in the second we can choose $\theta' + \pi$ (rotating the apparatus), in the third, $\theta' + \pi/2$ (performing a new rotation), for instance, and so on. Strictly speaking, we have more equations than unknowns. Actually, for each orientation of the experimental apparatus we have a different equation. But the experimental evidence we have so far seems to indicate that the quantum entanglement holds for arbitrary distances, which strongly suggests that entangled particles constitute a single entity ($\mathbf{u} \rightarrow \infty$).

References

[1] L. C. Ryff, Einstein-Podolsky-Rosen (EPR) Correlations and Superluminal Interactions, arXiv:1506.07383 [quant-ph].

[2] Interviews with John Bell and David Bohm in The Ghost in the Atom, P. C. W. Davies and J. R. Brown (eds.), Cambridge University Press, Cambridge (1989).

[3] V. Scarani, N. Gisin, Phys. Lett. A 295, 167 (2002); V. Scarani, N. Gisin, Braz. J. Phys. 35, 328 (2005); J.-D. Bancal, et al., Nat. Phys. 8, 867 (2012); T. J. Barnea, et al.: Phys. Rev. A 88, 022123 (2013).

[4] Naturally, we may assume, tentatively, that $v = V_{\text{CMB}}$, where the acronym CMB refers to the Cosmic Microwave Background radiation, and $V_{\text{CMB}}$ is the velocity relative to the frame (supposedly $S$) in which this radiation propagates isotropically. This would allow us to determine which photon is “really” detected first (that is, which photon is first detected in $S$).

[5] For the sake of simplicity, we are assuming that the FTL interaction is triggered when the first photon is detected. But, strictly speaking, whether the triggering occurs at the polarizer or at the detector can be considered an open question.

[6] This suggests the possibility that an apparent random phenomenon in the laboratory frame may actually be the consequence of a deterministic process in the preferred frame.
[7] Strictly speaking, there can be no infinite speed, since infinite is a limit, not an actual value. If entangled particles are instantly connected this means that, somehow, they are a single entity, even if they are arbitrarily distant from each other.

[8] Pauli, W.: Theory of Relativity. Pergamon Press (1967).