Proposal For Testing Bell’s Conjecture

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Abstract

A simple nonlocal mechanism for Einstein-Podolsky-Rosen correlations inspired by Bell’s conjecture (according to which “behind the scenes something is going faster than light”) is suggested, and an experimental test is proposed.

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I. INTRODUCTION

EPR correlations [1] are important not only due to their potential applications in quantum computing and cryptography [2], but also from the standpoint of the foundations of quantum theory [3]. Physicists are divided on this mind-boggling phenomenon that suggests a nonlocal connection between entangled particles. Some, based on experimental loopholes, believe — as Einstein did — that a local theory will complete quantum mechanics [4], while others consider that realism has to be revised [5]; a few, following John Bell, think that “behind the scenes something is going faster than light” [6]; many, agreeing with Asher Peres, advocate the straightforward application of the quantum mechanical formalism with no need for any metaphysical interpretation [7], and a not inconsiderable fraction probably simply ignores the problem [8]. Among those showing some sympathy for a nonlocal interaction approach are Gisin [9], and Leggett [10]. Bell and Bohm were very explicit about the possible existence of some kind of superluminal interaction [11], and the former has made it very clear that the assumption of a preferred frame of reference is not necessarily inconsistent with Lorentz transformations [12]. In this paper, inspired by the ideas of Bell, I will suggest a simple mechanism that might be behind these strange correlations and show how it could be checked.

In an attempt to investigate Bell’s conjecture, I will assume (considering a two-photon entangled state) that there must be some sort of wave, that I will
call a Bell-wave (or B-wave, for short), that propagates from the first detected photon (in the preferred frame) to the second, "forcing" it into a well-defined state (although the natural candidate responsible for the unleashing of this process is the detection of the first photon, other possibilities will be discussed in Sec. III). I will also assume, as a working hypothesis, that this B-wave can interact with physical objects, such as beam splitters, mirrors, phase shifters, polarizers and so forth, such that a nonstatic experiment might lead to totally different results from a static experiment. To develop this idea further, it is necessary to examine two important experimental tests of Bell's inequalities that used time varying analyzers.

The first one, uses acousto-optical switches [13]. Entangled photons, \( \nu_1 \) and \( \nu_2 \), from a source \( S \) can reach polarizers I and II, when the switches are in the transmission mode, and polarizers \( \text{I}' \) and \( \text{II}' \), when they are in the reflection mode. The second uses Pockels cells (\( C_1 \) and \( C_2 \) in Fig. 1) and two-channel polarizers, one in each arm of the experimental apparatus [14]. But now, differently from the first experiment, the switches work randomly as opposed to periodically. When the cell is activated this is equivalent to a rotation of the corresponding polarizer. The motivation for this type of experiment is to have the settings change during the time of flight of the particles so that no exchange of signals with velocity \( v \leq c \) could be responsible for the violations of Bell's inequalities [15]. The violation of a CHSH inequality [16] indeed discarded this possibility. The motivation behind the experiment I want to discuss is to have one of the switches in one mode when the photon passes through it coming from the source, and in another mode when the B-wave passes through it in the opposite direction coming from the detector. For instance, if \( C_1 \) is inactivated (activated) when \( \nu_1 \) impinges on it, it has to be activated (inactivated) when \( \nu_1 \) is detected (I am assuming that "detection" or, strictly speaking, "photon absorption", is an objective fact, independently of it being registered or not). But the changing of mode and the detection are space-like events, therefore their relative position in time depends on the Lorentz frame we use to observe them. It is easy to see (Sec. II) that there are an infinite number of frames in which the above condition is never satisfied. From Bell's nonlocal point of view, there must be a preferred frame in which one of these events really occurs before the other. But we do not know how to determine this frame. However, if the geometry of the experiment is changed so that the events become separated by a time-like interval, their relative position in time will be the same in all Lorentz frames. Now, in principle, they could be causally connected. Therefore, it is possible to know which event really occurred first. In the experiment represented in Fig. 2 the light path between \( C_1 \) (\( C_2 \)) and \( D_1 \) (\( D_2 \)) and \( D_1' \) (\( D_2' \)) has been made longer by means of a detour, so that, in any Lorentz frame, when \( \nu_1 \) (\( \nu_2 \)) is detected \( C_1 \) (\( C_2 \)) is already in a different state from that which it was in when \( \nu_1 \) (\( \nu_2 \)) passed through it (Sec. III) (naturally, now the activation of the cells cannot be randomic). If \( \nu_1 \) (\( \nu_2 \)) is detected first in the preferred frame, the B-wave goes from \( \nu_1 \) (\( \nu_2 \)) to \( \nu_2 \) (\( \nu_1 \)). Alternatively, we could have an asymmetric arrangement, in which the light path between \( S \) and \( D_2 \) (\( D_1 \)) and \( D_2' \) (\( D_1' \)) would be made longer, so that \( \nu_2 \) (\( \nu_1 \)) would always impinge on the
polarizer after the detection of $\nu_1 (\nu_2)$ (Fig. 3). In this case, the B-wave would always go from $\nu_1 (\nu_2)$ to $\nu_2 (\nu_1)$. If the mechanism suggested here is correct, we will no longer observe the correlations predicted by quantum mechanics.

II. NONSTATIC TESTS OF BELL’S INEQUALITIES SEEN FROM MOVING FRAMES

I will discuss the experiment of ref. 14, though the same argumentation can be used for the experiment of ref. 13. We can consider a specific situation. Let $t_0 = 0$ be the instant at which $\nu_1$ and $\nu_2$ are emitted in laboratory frame $L$ (Fig. 1), $t_{C_1} (t_{C_2})$ the instant at which $C_1 (C_2)$ completely changes (after the passage of the photon) from the i-mode (inactivated), to the a-mode (activated), and $t_1 (t_2)$ the instant at which $\nu_1$ and $\nu_2$ are absorbed at detectors $D_1$ and $D_2$ (a similar reasoning would be valid for $D_1'$ and $D_2'$). I will assume that when the photons are detected the switches are already in the a-mode. But, as can easily be seen, there are an infinite number of Lorentz frames in which they are still in the i-mode. For example, let us observe the experiment from a frame $L'$ moving in the same direction as $\nu_1$ with velocity $v$. Let $t'_0 = 0$ be the instant at which the photons are emitted in $L'$. Hence, the instants at which $C_1$ and $C_2$ change completely are given by

$$t'_{C_1} = \gamma \left( t_{C_1} - \frac{v}{c^2} x \right)$$

(1)

and

$$t'_{C_2} = \gamma \left( t_{C_2} + \frac{v}{c^2} x \right)$$

(2)

where $\gamma = 1/\sqrt{1 - v^2/c^2}$, $x$ ($-x$) is the distance from the source $S$ to $C_1$ ($C_2$), and I am assuming that $L$ and $L'$ are in the standard configuration. For the instants at which $\nu_1$ and $\nu_2$ are absorbed we obtain

$$t'_1 = \gamma \left( t - \frac{v}{c^2} x \right)$$

(3)
and
\[ \bar{T}_2 = \gamma \left( \bar{t} + \frac{v}{c^2} \bar{x} \right), \]
where \( \bar{t} (-\bar{x}) \) is the distance from \( S \) to \( D_1 \) \((D_2) \). To have \( \nu_1 \) detected before \( C_1 \) changes to the a-mode, the condition
\[ \bar{t}_1 < t'_{C_1} \]
must be fulfilled, which leads, using (1) and (3), to
\[ v > c \left( \frac{\bar{t} - t_{C_1}}{t_f} \right), \]
where \( t_f = (\bar{t} - x)/c \) is the time the photon takes to go from \( C_1 \) to \( D_1 \). In a frame moving with a velocity that satisfies condition (6) \( \nu_1 \) will be detected before \( C_1 \) changes its state. For \( \nu_1 \) to be detected before \( C_2 \) changes to the a-mode, the following condition must be fulfilled:
\[ \bar{t}_1 < t'_{C_2}. \]
Since \( t_{C_2} \approx t_{C_1} \), we see from (1) and (2) that (5) implies (7). (It is easy to see that (7) leads to \( v > c \times (\bar{t} - t_{C_2}) / T_f \), where \( T_f = (\bar{t} + x)/c \).)

III. A PROPOSED EXPERIMENT

The experiment represented in Fig. 2 is different from the experiment of ref. 14 in two respects: there is a detour in each photon path and the switches work periodically. Initially, I will consider the following situation. Photon \( \nu_1 \) (the same reasoning is valid for \( \nu_2 \)) reaches \( C_1 \) when it has just entered the i(a)-mode. Let \( \Delta t \) be the duration of each mode, and \( t_f \) the time taken by \( \nu_1 \) to go from \( C_1 \) to \( D_1 \). The condition that the detection of \( \nu_1 \) really occurs after \( C_1 \) has already completely changed to the a(i)-mode can be expressed as [17]
\[ \Delta t + t_f < \bar{t}_f, \]
since, after the passage of the photon, \( C_1 \) takes a time interval of \( \Delta t \) to change completely from the i(a)-mode to the a(i)-mode, and an imaginary light beam sent from \( C_1 \) at this moment would take time \( t_f \) to reach \( D_1 \) following a straight line. According to (8), this light beam would reach \( D_1 \) before \( \nu_1 \). But,
\[ \bar{t}_f = t_f + \frac{2y}{c}, \]
where \( y \) is the height of the detour. Using (8) and (9), we obtain the following condition that our experiment has to fulfil:
\[ y > \frac{c \Delta t}{2}. \]
Figure 2: The proposed experiment. (The relative sizes do not correspond to that of an actual experiment.)

It is also necessary that when $\nu_1$ is detected $C_1$ has not yet returned to the i(a)-mode. The condition that the detection of $\nu_1$ really occurs before $C_1$ has already returned to the i(a)-mode can be expressed as

$$\bar{t}_f + t_f < 2\Delta t. \quad (11)$$

Using (9) and (11), we also obtain

$$y < c\Delta t - ct_f. \quad (12)$$

Then, (10) and (12) lead to

$$t_f < \frac{\Delta t}{2}. \quad (13)$$

But, $t_f = (\bar{\tau} - x)/c$, where $\bar{\tau} - x$ is the distance between $C_1$ and $D_1$. So, we must also have

$$\bar{\tau} - x < \frac{c\Delta t}{2}. \quad (14)$$

Let us now consider the situation in which $\nu_1$ reaches $C_1$ just before it leaves the i(a)-mode. Now, instead of (8) we have $t_f < \bar{t}_f$, which is always satisfied. We see that, if condition (10) is fulfilled, all photons, independently of the instant they reach $C_1$, will be detected after the change from the i(a)-mode to the a(i)-mode. On the other hand, instead of (11) we have $\bar{t}_f + t_f < \Delta t$. Then using (9), we obtain $2y < c\Delta t - 2ct_f$, which is inconsistent with (10). A possible way to overcome this difficulty is to try to synchronize the emission of the photons with the activation and inactivation of the switches, such that the photons will always reach the switches when they have just entered a mode. In this case, conditions (10), (12) and (14) will be satisfied.

Another way to overcome the difficulty is based on a compromise solution. For example, let us consider the photons $\nu_1$ that reach $C_1$ when it has already spent a time equal to $9\Delta t/10$ in the i(a)-mode. Then, instead of (8), we must have

$$\frac{\Delta t}{10} + t_f < \bar{\tau}_f, \quad (15)$$
which leads, using (9), to
\[ y > \frac{c\Delta t}{20} \]  
(16)

Therefore, if (10) is satisfied, this is also true for (16). On the other hand, instead of (11) we must have
\[ t_f + t_f < \frac{\Delta t}{10} + \Delta t, \]
(17)

which leads, using (9), to
\[ y < \frac{11c\Delta t}{20} - ct_f. \]  
(18)

Hence, using (10), we obtain
\[ t_f < \frac{\Delta t}{20} \]  
(19)

and
\[ \pi - x < \frac{c\Delta t}{20}, \]  
(20)

which is more restrictive than (14). If conditions (10), (18) and (20) are fulfilled, 90\% of the photons will effectively reach the switches when they are in the i(a)-mode, and will be detected when they are in the a(i)-mode. Using logic circuits [14], the other 10\% of the events, that correspond to the photons that reach the switch when it has already spent a time greater than 9\Delta t/10 in the i(a)-mode, can be disregarded.

Although I have only discussed detections at D₁, it is easy to see that, if the distance from C₁ to D₁′ is smaller than the distance from C₁ to D₁, as in the scheme represented on Fig. 2, then the deduced conditions contain those for detections at D₁′. Detections "without a click" [18] are also included. With respect to this point, it is interesting to observe that, if D₁′ is in the "right position, the condition (20) for D₁ does not need to be fulfilled, since (considering the situation in which both photons are detected) the lack of detection at D₁′ is equivalent to a detection at D₁ in the "right" position (in ideal situations, this is true even if D₁ has been removed!) It is also easy to see that the assumption that the B-wave is triggered by the splitting of the photon at the polarizer into a "photonic" and an "empty" wave — which is consistent with the pilot wave interpretation [19] — leads to conditions that are also contained in those that have been obtained. In the event of corroboration of Bell’s conjecture, the proposed experiment can be modified in order to determine where and when the collapse of the state vector (the triggering of the B-wave, in the present case) takes place: in the polarizer, when the photon is split, or in the detector, when it is annihilated (or when it is not, if we have detection without a click). For this, we can place the detours between the polarizers and the detectors. If the results agree (disagree) with the predictions of quantum mechanics, the first (second) possibility is the correct one.

In conclusion, the strong correlations displayed by twin photons, which result from entanglement, suggests, as strangely as this may sound, a nonlocal connection between these photons. This point has been emphasized by Bell, according
to whom "behind the scenes something is going faster than light". A simple mechanism for this process, suggested here, can be experimentally tested by means of a straightforward modification of two experiments already performed to test the CHSH inequality. Although only qualitative predictions are being made, this kind of approach is not foreign to physics, and is in agreement with its investigative nature, the best example being the discovery of the law of electromagnetic induction by Faraday [20]. However, for the sake of completeness, a simple nonlocal model that yields quantitative predictions is discussed in the Appendix.

APPENDIX: A SIMPLE NONLOCAL MODEL

The following nonlocal model bears some resemblance to the advanced wave interpretation [21], though now the detector that has really "clicked" first effectively emits a B-wave. It is easier to discuss the experiment represented in Fig. 3. Now $\nu_1$ is always detected before $\nu_2$, and the conditions obtained in Sec. III are valid for it. As an example, I will consider a specific situation; other situations can be treated in a similar way. Both polarizers are oriented vertically, and the Pockels cell $C_1$, when activated, rotates the polarization of light by an angle $-\theta$. Let us represent the two-photon entangled state emitted by $S$ as $|\Psi\rangle = 1/\sqrt{2} (|V\rangle_2 |H\rangle_1 - |H\rangle_2 |V\rangle_1)$ [22]. To be in agreement with the quantum mechanical predictions for the static case (i.e., when $C_1$ is permanently either activated or inactivated) I will assume that the B-wave emitted by $D_1(D_1')$ emerges from the polarizer in "state" $|V\rangle_B \equiv |0\rangle_B (|H\rangle_B \equiv |\pi/2\rangle_B)$ [23]; then, passing through $C_1$, it emerges either in the same state (if $C_1$ is inactivated) or in state $|\theta\rangle_B (|\pi/2 + \theta\rangle_B)$ (if $C_1$ is activated). In this respect, the B-wave behaves like an ordinary electromagnetic wave. It then goes into the source and emerges in an orthogonal polarization state [24]. This is the state into which $\nu_2$ will be forced, if no other optical devices are on the path of the B-wave. I will further assume that the these rules are still valid in the nonstatic case.
Let us then examine the situation in which $\nu_1$ passes through $C_1$ when it is inactivated. From the standpoint of quantum mechanics the detection probabilities do not depend on which photon is detected first. The probability of having $\nu_2$ detected in the state $|V\rangle$ is $1/2$, in which case $\nu_1$ will be forced into the state $|H\rangle$, and the probability of having both photons transmitted will be $(P_{21})_Q = 0$. On the other hand, from the nonlocal point of view introduced here, $C_1$ will be activated for the B-wave, since $\nu_1$ is effectively detected first, and we will have: $|V\rangle_B \rightarrow |\theta\rangle_B$, after $C_1$, and $|\theta\rangle_B \rightarrow |\frac{\pi}{2} + \theta\rangle$, after $S$, which leads to $(P_{21})_B = \frac{1}{2} \sin^2 \theta$.

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