Quantum Nonlocality and Indistinguishability

Luiz Carlos Ryff

Instituto de Física, Universidade Federal do Rio de Janeiro,
Caixa Postal 68528, 21041-972 Rio de Janeiro, Brazil
E-mail: ryff@if.ufrj.br

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Abstract

It is shown how a “meddlesome” photon indistinguishable from another photon of an entangled pair can affect the result of an Einstein-Podolsky-Rosen (EPR) experiment. This makes it clear the importance of the notion of field over that of particle.

Key words: EPR correlations; entangled states; Bell’s inequality; special relativity

Quantum nonlocality, in which acting on a particle of an entangled pair we can “force” [1] the other into a well-defined state, is one of the amazing consequences of quantum formalism. This can be accomplished via EPR correlations [2]. Although it has been confirmed by experiment, its interpretation is still a matter of dispute. For Bell [3] and Bohm [4] there should be some kind of interaction between the particles, but not all physicists share the same point of view [5]. Experiments have been performed to try to determine a lower limit to the speed of this possible interaction [6], and it has been demonstrated that if this speed is finite then superluminal signaling would be possible, at least in principle [7]. Quantum teleportation [8] and entanglement swapping [9] are important offsprings of quantum nonlocality. Actually, as has been shown, in certain circumstances the very same phenomenon can be seen as quantum teleportation, as entanglement swapping, or as usual EPR correlation, depending on the Lorentz frame from which it is observed [10].

Indistinguishability plays a crucial role in quantum mechanics. In classical physics two particles, even being identical, have independent identities, which is reflected in Maxwell–Boltzmann statistics. On the other hand, this is not true in quantum mechanics, which leads to Bose-Einstein and Fermi-Dirac statistics. In fact, the very concept of particle is somewhat diffuse in this case. Lamb duly criticized the idea of photon [11], and we have to be careful not to say (as occurs with some frequency) that a quantum particle (which may be a photon, an electron, an atom, and even a molecule) can be at two different places at the same time (as in a two-slit experiment, for instance). To avoid some apparent paradoxical conclusions [12] it would be advisable to keep Ketterle teaching
in mind: we prepare waves and detect particles [13]. I intend to discuss a consequence of the mathematical formalism of quantum mechanics here, which involves quantum nonlocality and indistinguishability, that corroborates this point of view. Although it is a simple result, to my knowledge it has not been previously discussed in the literature and may have important consequences for questions related to interpretational matters, and possibly to the field of quantum communication as well.

Let us consider the experiment represented in Fig.1. A source $S$ emits pairs of photons in the polarization-entangled state

$$|\varphi\rangle = \frac{1}{\sqrt{2}} (|a_{\parallel}\rangle_1 |a_{\parallel}\rangle_2 + |a_{\perp}\rangle_1 |a_{\perp}\rangle_2),$$

where $|a_{\parallel}\rangle_1 (|a_{\perp}\rangle_1)$ represents a photon $\nu_1$ with linear polarization $a$ ($a_{\perp}$) (and so on). Photon $\nu_1$ ($\nu_2$) impinges on polarizer $I$ ($II$), oriented parallel to $b$ ($a$). Photon $\nu_1$ [14] follows via a detour, so that the detections of $\nu_1$ and $\nu_2$ are time-like events. The importance of considering time-like events when discussing EPR correlations has previously been stressed [15]. This allows us to know which measurement really forces the other photon into a well-defined polarization state. (Here the word “measurement” is an abuse of language, since the photon has no previous polarization to be measured. Actually, the measurement forces the photon into a well-defined polarization state.) A photon $\nu_3$ with linear polarization $c$ (except for its polarization state, in all respects identical to $\nu_2$) impinges on polarizer $III$. For argumentation purposes, it is sufficient to consider the situation in which detections at 2 and 3 occur at the same time.

![Diagram](image-url)}
in the laboratory frame [16]. In this case, it is not possible to know whether \( \nu_2 \) has been transmitted or reflected at polarizer II. We could be led to infer (erroneously, as we will see) that \( \nu_1 \) will always impinge on polarizer I either in state \(|a, l\rangle\) or state \(|a, m\rangle\), since \( \nu_2 \) will necessarily be transmitted or reflected. However, according to the mathematical formalism of quantum mechanics, by playing with the initial polarization state of \( \nu_3 \), we can force \( \nu_1 \) into different polarization states. This result may be interpreted as corroborating the standpoint that ascribes an essential role to information in quantum mechanics. But this information has to be seen as corresponding to an objective fact, that can be translated into subjective knowledge. Amazingly, the formalism of quantum mechanics gives us no hint about how nature deals with this information: How does nature “know”? How is the information conveyed? These are questions that do not seem to have a simple answer. Let us then see what mathematical formalism has to say in the present case.

The initial three photon state can be represented as

\[
|\psi\rangle = N \left[ \left( |a, l\rangle |a, m\rangle + |a, l\rangle |a, m\rangle \right) |c, q\rangle + ST \right],
\]

(2)

where \(|a, m\rangle = |a, l\rangle_1 |a, m\rangle_2, |a, l\rangle |a, m\rangle = |a, l\rangle_1 |a, m\rangle_2\) and \(|c, q\rangle = |c, q\rangle_3\), and \(l, m,\) and \(q\) represent the paths followed by the photons. \(ST\) stands for Symmetric Terms, and \(N\) is a normalization factor. The time evolution of the system is given by

\[
|\psi\rangle_{pol.II,pol.III} \longrightarrow N \left\{ \left( |a, l\rangle |a, n\rangle + |a, l\rangle |a, p\rangle \right) \left[ \cos (a, c) |a, r\rangle + \sin (a, c) |a, s\rangle \right] + ST \right\} = |\psi'\rangle
\]

(3)

and

\[
|\psi'\rangle_{H_2,H_3} \longrightarrow N \left\{ \left( |a, l\rangle |2\rangle + |a, l\rangle |3\rangle \right) \left[ \cos (a, c) |2\rangle + \sin (a, c) |3\rangle \right] + \ldots + ST \right\} = |\psi''\rangle.
\]

(4)

Here, \(|2\rangle\) represents a photon following direction 2 and so on, and \(H_2\) and \(H_3\) are 50%-50% beam-splitters. Hence,

\[
|\psi''\rangle = N \left[ \sin (a, c) |a, l\rangle |2\rangle |3\rangle + \cos (a, c) |a, l\rangle |2\rangle |3\rangle \right] + \ldots + ST\right].
\]

(5)

Now, taking into account the \(ST\), we can write:

\[
|\psi''\rangle = N \left[ \sin (a, c) |a, l\rangle |2\rangle |3\rangle + \cos (a, c) |a, l\rangle |2\rangle + \ldots \right].
\]

(6)

Therefore, whenever coincident detections occur at 2 and 3, \(\nu_1\) is forced into state

\[
|\varphi'\rangle = \sin (a, c) |a, l\rangle + \cos (a, c) |a, l\rangle.
\]

(7)

This is a simple and interesting result (naturally, other coincident detections can be managed in a similar way). If we remain too closely attached to the photon picture, (7) may look paradoxical. One may be led to reason as follows: If \(\nu_2\) is detected at 2 (3) it has been transmitted (reflected), which would imply,
according to (1), that $\nu_1$ has been forced into state $|a\rangle (|a_\perp\rangle)$. But a photon has no individuality, and it is not possible to know where $\nu_2$ has really been detected (actually, this question has no meaning). The realization of the experiment that has been discussed here would be an impressive and palpable demonstration of the indistinguishability of photons, and would corroborate the point of view that emphasizes the importance of the notion of field over that of particle.

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The interesting article by A. Hobson, *Am. J. Phys.* 81, 211 (2013), emphasizing the notion of field over that of particle is worth reading. Actually, the idea of photon can be useful, provided we use it wisely.

In a popular talk about the Bose-Einstein condensate, given at the annual meeting of the German Physical Society in Hannover in March 2003, the Nobel prize winner Wolfgang Ketterle told the public that it is very hard to understand quantum mechanics, but after several years of physical practice one gets used to preparing waves and detecting particles. (See, B. Falkenburg, *Particle Metaphysics*, Springer, Berlin (2007), p.280).

Here the term photon is a useful abuse of language. It refers to a Fock state of occupation number one. We have to keep in mind that we are considering a physical entity that propagates as a wave and is detected as a particle. Actually, this is the big quantum mystery, the reduction of the state vector (collapse of the wave function), which is connected to quantum nonlocality.

Strictly speaking, the detections don’t need to be simultaneous, provided it is impossible to know which photon is detected at which place. Actually, it is always possible to describe the experiment from a Lorentz moving frame in which the events are no longer simultaneous. Naturally, to define “simultaneous” we have to take into account the lengths of the wave packets associated to the photons.