Quasi-gedanken experiment challenging the no-signaling theorem

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Abstract. Kennedy [*Philosophy of Science* 62, 4 (1995)] has argued that the various quantum mechanical no-signaling proofs formulated thus far share a common mathematical framework, are circular in nature, and do not preclude the construction of empirically testable schemes wherein superluminal exchange of information can occur. In light of this thesis, we present a potentially feasible quantum-optical scheme that purports to enable superluminal signaling.

Keywords. quantum information, quantum entanglement, no-signaling theorem

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1. Introduction

The notion of *quantum non-locality* resides at the core of the interpretation of multi-particle entanglement ([1], [2], [3]) because of the great amount of empirical evidence, in support of this notion, that has been acquired thus far (mostly from the realm of quantum optics [4]). Nevertheless, the physical manifestations of quantum non-locality are constrained by seemingly robust theoretical precepts demanding that non-local effects cannot be used for the construction of any type of superluminal signaling protocol employing the quantum mechanical formalism (as it is currently understood). The theoretical arguments against superluminal exchange of information are articulated by way of 'no-signaling theorems' [5,6,7,8,9,10,11].

We will describe a potentially feasible quantum-optical scheme that purports to enable superluminal signaling. The quest for such a scheme was largely motivated by the critical analysis of the various no-signaling proofs by Kennedy [12], wherein he rigorously argues that they share a common mathematical framework and that they are, in fact, circular in nature (tautological), leaving a bit of room for the possibility of constructing superluminal signaling protocols within the context of non-relativistic quantum mechanics. We present a setup that can be viewed as a 'quasi-gedanken experiment', in the sense that most of its constituent devices are readily available and have been employed in many quantum-optical experiments, however the device that performs the crucial function has not been specified but, as will become evident, certainly appears to be within the reach of existing technology.

2. Experimental Proposal

Consider the setup of Fig.1. An *SPDC* (spontaneous parametric down-conversion) source, *S*, of entangled photon pairs is pumped by a *CW* (continuous-wave) laser [4]. We assume that the pump intensity is low enough so that only single pairs of entangled photons are produced from *S* with any significant probability and, furthermore, that *S* is configured for degenerate, non-collinear emission of polarization-entangled photon pairs [4]. We can write the state emerging from *S* as

$$(1) \qquad |\Psi_S\rangle = \frac{1}{\sqrt{2}}(|H_A\rangle|H_B\rangle + |V_A\rangle|V_B\rangle) ,$$

where *H* and *V* denote the horizontal and vertical linear-polarization states of an emitted photon, respectively; the subscripts *A* and *B* denote the two spatial modes of emission.

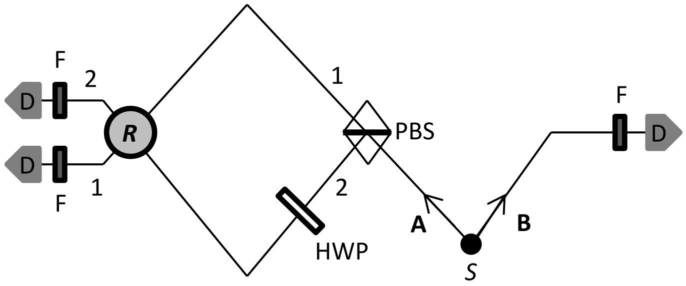

Fig.1. Source S produces polarization-entangled photon pairs into modes A and B. Left-propagating photons are subject to a polarizing beam splitter (PBS) and a half-wave plate (HWP) before they enter region R, wherein a Demon performs activities that induce non-local effects on the quantum state of right-propagating photons. Every photon pair is spectrally filtered by narrow-band filters, F, and registered by detectors, D.

Fig.1 depicts the presence of narrow-band spectral filters, *F*, whose narrow transmission band is centered on an energy that is half that of the pump photons. A detector, *D*, is situated immediately beyond each filter. Therefore, for each detected down-converted photon pair that made it past the filters, both of its constituent photons will be found to have the same energy (equal to half that of the pump photons).

From Fig.1 we note that the photons propagating within the left wing of the setup first encounter a *PBS* (polarizing beam splitter) and then an *HWP* (half-wave plate). The *PBS* transmits H-polarized photons and reflects V-polarized photons, while the *HWP* flips the linear-polarization state. Thus, after the *PBS* and *HWP*, the state $|\Psi_S\rangle$ transforms as follows:

$$(2) \qquad |\Psi_S\rangle \xrightarrow{PBS/HWP} \frac{1}{\sqrt{2}}(|H_1\rangle|H_B\rangle+|H_2\rangle|V_B\rangle)\equiv |\Psi_R\rangle.$$

Focusing on the left wing of the setup, Fig.1 indicates a region, *R*, wherein we will postulate that a Demon resides. The Demon within *R* performs the following activity: For a certain time interval, he inserts a *double-sided mirror* (*DSM*) so that mode *1* is reflected into mode *2*, and mode *2* is reflected into mode *1*, each reflected mode acquiring a reflection phase-shift factor $e^{i\varphi}$. Immediately afterwards, the Demon inserts, for the same time interval, a suitably chosen *transparent phase plate* (*TPP*) such that both transmitted modes, *1* and *2*, each acquire a transmission phase-shift factor $e^{i\varphi}$. The Demon repeats this switching action continuously.

In (2), $|\Psi_R\rangle$ represents the state beyond the *PBS* and *HWP*, as the left-propagating photon is about to enter region *R*. If the *DSM* is in place within *R*, the state beyond *R* becomes

$$(3) \qquad |\Psi_R\rangle \xrightarrow{DSM} \frac{1}{\sqrt{2}}(e^{i\varphi}|H_2\rangle|H_B\rangle + e^{i\varphi}|H_1\rangle|V_B\rangle) \equiv |\Psi_{DSM}\rangle.$$

If the *TPP* is in place within R, the state beyond R becomes

$$(4) \qquad |\Psi_R\rangle \xrightarrow{TPP} \frac{1}{\sqrt{2}}(e^{i\varphi}|H_1\rangle|H_B\rangle + e^{i\varphi}|H_2\rangle|V_B\rangle) \equiv |\Psi_{TPP}\rangle.$$

Now, before we can illustrate the purported superluminal-signaling potential of the setup, we must first impose specific requirements on parameters that characterize certain quantum-optical properties involved. In this light, we will assume a hierarchy of ‘realistic’ parameter-values for several aspects of the setup, gleaned from the plethora of quantum-optical entanglement experiments that have been carried out thus far: The coherence-time of the pump laser is taken to be *infinite*, since the pump laser is considered to be monochromatic; the coherence-time of the down-converted photons, emerging from the *SPDC* source, is taken to be around *0.1ps*, since they are typically broad-band; the Demon’s switching interval, between the *DSM* and the *TPP*, is taken to be *1ps*; the coherence-time of the down-converted photons that have been spectrally filtered by the narrow-band filters, *F*, is taken to be around *10ps*. Once we have accepted these parameter-values, we can make the following assertion:

Since the filters, *F*, have 'stretched' the coherence-time of the down-converted photons from *0.1ps* (just before the filters) to *10ps* (for the subset that has been spectrally filtered and propagates towards the respective detectors), the accuracy of their *time-of-creation* (within source *S*) is also limited to *10ps* and thus it is not possible, *even in principle*, to determine if a left-propagating photon encountered the *DSM* or the *TPP*, since the switching interval is *1ps*. This assertion demands that we must *superpose the two indistinguishable possibilities* leading to detections of down-converted photon pairs beyond the filters:

$$\begin{aligned} (5) \qquad |\Psi_M\rangle &= \frac{1}{\sqrt{2}}(|\Psi_{DSM}\rangle + |\Psi_{TPP}\rangle) \\ &= e^{i\varphi}\frac{1}{\sqrt{2}}(|H_1\rangle\frac{1}{\sqrt{2}}|H_B+V_B\rangle + |H_2\rangle\frac{1}{\sqrt{2}}|H_B+V_B\rangle) \\ &= e^{i\varphi}\frac{1}{\sqrt{2}}(|H_1\rangle|+_B\rangle + |H_2\rangle|+_B\rangle), \end{aligned}$$

where $|+_B\rangle \equiv \frac{1}{\sqrt{2}}|H_B+V_B\rangle$. In (5), $|\Psi_M\rangle$ represents the *normalized* state that will be subject to measurement (*i.e.*, the state beyond the filters and just before the detectors). At this point it is essential to note the fact that expression (5) is *non-standard*, in the sense that it embodies a non-unitary transformation: Two orthogonal state vectors ($|H_1\rangle$ and $|H_2\rangle$, pertaining to the left wing of the setup) induce a projection (upon their measurement) onto a single state vector ($|+_B\rangle$, pertaining to the right wing of the setup). In addition to being non-standard, we must also stress that expression (5) was posited solely on the heuristic notion of quantum mechanical ‘indistinguishability’ and, therefore, it remains to be seen if this state-vector transformation is allowed by quantum optics (implying that there would have to exist latent elements in the Fock-space algebra that go beyond the standard Hilbert-space formalism).

Indeed, the remarkable feature of $|\Psi_M\rangle$ is that the right-propagating photon is *always* projected onto the linear-polarization state $|+_B\rangle$ regardless of whether its partner photon was detected in mode *1* or *2* (on the left wing of the setup). So, if the Demon performs the switching activity, then the state on the right wing of the setup is always found to be $|+_B\rangle$, whereas if the Demon just held, say, the *DSM* fixed in place, then the state on the right wing of the setup would just be an incoherent 50/50 mixture of the $|H_B\rangle$ and $|V_B\rangle$ states (as can be inferred from (3), where the state $|\Psi_{DSM}\rangle$ is explicitly shown). These two distinct states obtained on the right wing, as a function of the two specified behaviors of the Demon on the left wing, are in fact *distinguishable* by an observer on the right wing and, therefore, a protocol for superluminal signaling may be constructed.

3. Superluminal Signaling

The Demon can encode the information bits ‘*0*’ and ‘*1*’ by defining a fixed time interval within which a batch of detections occur and, depending on what bit he wants to transmit, he chooses whether he will leave the *DSM* in place during the fixed time interval (‘*0*’ bit, resulting in measurement statistics on the right wing corresponding to the $|H_B\rangle/|V_B\rangle$ incoherent mixture) or perform the switching activity during the fixed time interval (‘*1*’ bit, resulting in measurement statistics on the right wing corresponding to the pure state $|+_B\rangle$). By concatenating any number of such fixed time intervals, the Demon, on the left wing, can transmit a message to the right wing of the setup. In order for the message to be truly superluminal, the fixed time interval chosen to manifest the ‘*0*’ or ‘*1*’ bit must be brief enough to ensure space-like separation between the left and right wings of the setup. In other words, the encoding of a bit (on the left wing) should be completed before any other causal signal can reach the right wing. Furthermore, we must stipulate that the detectors on the left and right wings of the setup are configured to properly record events: The two photons comprising each *SPDC* pair are created virtually simultaneously at a very localized (point-like) region within the source and their strict energy correlation (due to the *CW* monochromatic pump) ensures that a detection of a photon on the left wing will always be accompanied by the detection of its partner photon on the right wing, provided the detection ‘gate time’ and detector synchronizations are suitably chosen with respect to the *SPDC* emission rate and geometry of the setup.

4. Conclusion

In conclusion, we have described a quantum-optical setup that purports to evade the constraints of the no-signaling theorem, allowing superluminal transmission of information. The setup appears to be feasible, but perhaps is best described as a quasi-gedanken experiment because of the, as yet, unspecified physical device that will perform the activity of the Demon. It remains to be seen if the scheme is flawed, or if it points to some deficiency in the standard quantum mechanical formalism, or if it indeed implies the existence of latent superluminal signaling protocols within the current theoretical framework of quantum mechanics [13,14].

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