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Rapid Communication: Quasi-gedanken experiment challenging the no-signalling theorem

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Abstract. Kennedy (*Philos. Sci*. **62**, 4 (1995)) has argued that the various quantum mechanical no-signalling 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 signalling.

Keywords. Quantum information; quantum entanglement; no-signalling theorem.

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1. Introduction

The notion of 'quantum non-locality' resides at the core of the interpretation of multiparticle entanglement [1–3] 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 signalling 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-signalling theorems' [5–11].

We shall describe a potentially feasible quantum-optical scheme that purports to enable superluminal signalling. The quest for such a scheme was largely motivated by the critical analysis of the various no-signalling 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 signalling protocols within the context of non-relativistic quantum mechanics. We present a set-up 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 set-up of figure 1. A spontaneous parametric down-conversion (SPDC) source, S, of entangled-photon pairs is pumped by a continuous-wave (CW) 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 polarisation-entangled photon pairs [4]. We can write the state emerging from S as

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

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

Figure 1 depicts the presence of narrow-band spectral filters, F, whose narrow transmission band is centred 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

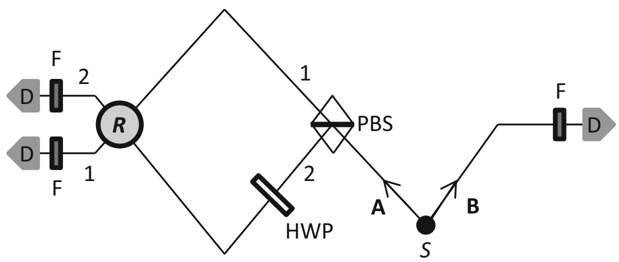

Figure 1. Source S produces polarisation-entangled photon pairs into modes A and B. Left-propagating photons are subjected to a polarising beam splitter (PBS) and a half-wave plate (HWP) before they enter region R, wherein a Demon performs activities that induce non-local effects on the quantum state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

photons will be found to have the same energy (equal to half that of the pump photons).

From figure 1 we note that the photons propagating within the left wing of the set-up first encounter a polarising beam splitter (PBS) and then a half-wave plate (HWP). The PBS transmits H-polarised photons and reflects V-polarised photons, while the HWP flips the linear polarisation state. Thus, after the PBS and HWP, the state $|\Psi_S\rangle$ transforms as follows:

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

Focussing on the left wing of the set-up, figure 1 indicates a region, R, wherein we shall 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

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

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

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

Now, before we can illustrate the purported superluminal-signalling potential of the set-up, we must first impose specific requirements on the parameters that characterise certain quantum-optical properties involved. In this light, we shall assume a hierarchy of 'realistic' parameter values for several aspects of the set-up, 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, because 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 0.1 ps, as they are typically broadband; the Demon's switching interval between the DSM and the TPP is taken to be 1 ps; the coherence time of the down-converted photons that have been spectrally filtered by the narrow-band filters, F, is taken to be around 10 ps. Once we have accepted these parameter-values, we can make the following assertion.

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

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

where $|+_B\rangle \equiv \frac{1}{\sqrt{2}}|H_B + V_B\rangle$. In (5), $|\Psi_M\rangle$ represents the normalised state that will be subjected 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 set-up) induce a projection (upon their measurement) onto a single state vector ($|+_B\rangle$, pertaining to the right wing of the set-up). 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 $|\Psi_{\mathrm{M}}\rangle$ is that the right-propagating photon is always projected onto the linear polarisation state $|+_{\mathrm{B}}\rangle$ regardless of whether its partner photon was detected in mode 1 or 2 (on the left wing of the set-up). So, if the Demon performs the switching activity, then the state on the right wing of the set-up is always found to be $|+_{\mathrm{B}}\rangle$, whereas if the Demon just held, say, the DSM fixed in place, then the state on the right wing of the set-up would just be an incoherent 50/50 mixture of the $|H_{\mathrm{B}}\rangle$ and $|V_{\mathrm{B}}\rangle$ states (as can be inferred from (3), where the state $|\Psi_{\mathrm{DSM}}\rangle$ is explicitly shown). These two distinct states obtained on the right wing, as a function of the two specified behaviours of the Demon on the left wing, are in fact distinguishable by an observer on the right wing and, therefore, a protocol for superluminal signalling may be constructed.

3. Superluminal signalling

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 $|H_{\mathrm{B}}\rangle/|V_{\mathrm{B}}\rangle$ 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 $|+_{\mathrm{B}}\rangle$). 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 set-up. 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 set-up. 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 set-up are configured to properly record the events: The two photons comprising each SPDC pair are created virtually simultaneously at a very localised (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 synchronisations are suitably chosen with respect to the SPDC emission rate and geometry of the set-up.

4. Conclusion

In conclusion, we have described a quantum-optical set-up that purports to evade the constraints of the various no-signalling theorems put forth to date, allowing superluminal transmission of information. The set-up 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 signalling protocols within the current theoretical framework of quantum mechanics [13,14].

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