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A Scrutiny of Landmark Experiments Disproves Photonic Quantum Nonlocality

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Abstract: A physical scrutiny of experimental results published in Physical Review Letters (December 2015, M. Giustina, *et al*., Phys. Rev. Lett. **115**, 250401, and L. K. Shalm *et al*., Phys. Rev. Lett. **115**, 250402) is undertaken. These articles reported that measured outcomes were fitted with quantum states possessing a dominant component of non-entangled photons, thereby contradicting their own claim of quantum nonlocality. With probabilities of photon detections lower than 0.1 %, the alleged quantum nonlocality cannot be classified as a resource for developing quantum computing devices, despite recent publicity. Experimental evidence of a feasible process for quantum-strong correlations has been identified (M. Iannuzzi, *et al.,* Phys. Lett. A, **384** (9), 126200, 2020) in terms of correlations between independent and multi-photon states evaluated as Stokes vectors on the Poincaré sphere. As single-photon sources are not needed, the design and implementation of quantum computing operations will be significantly streamlined.

1. Introduction

Over the last two decades, large amounts of resources have been invested in the research and development of quantum computing based on the concept of quantum nonlocality. Yet, no such functional or operational device is expected in the near future. Nevertheless, photonic quantum nonlocality – despite being substantially rebutted in the professional literature, e.g. [1-9] – has been the subject of the 2022 Nobel Prize in Physics. Significant physical contradictions have been overlooked in the opinion article by Aspect [10] hailing the results of refs. [11] and [12] as "definitive proof" of one measurement influencing remotely another measurement, bringing about the end of the Einstein-Bohr debate.

Experimental evidence of strong-quantum correlations obtained with non-entangled photons [7] were published back in early 2020 but were overlooked because they did not fit the prevailing interpretation [10]. Equally, a growing body of analytic developments before and after 2015 have repeatedly demonstrated the statistical nature [1-3] of quantum nonlocality experiments. Recently, the physical impossibility of the concept of quantum nonlocality based on entangled photons has been pointed out [8-9].

The concept of quantum nonlocality was summarized by Aspect in the first paragraph of ref. [10] as "the idea that a measurement on one particle in an entangled pair could affect the state of the other—distant—particle." The alleged physical effect was illustrated for the entangled state

$$|\,\psi_{AB}\rangle = (|x\rangle_A\,|x\rangle_B + |y\rangle_A\,|y\rangle_B)/\sqrt{2} \qquad (1)$$

of two polarized photons shown in the inset to Fig. 1 of [10] for which "quantum mechanics predicts that the polarization measurements performed at the two distant stations will be strongly correlated." Another quotation of interest is: "In what are now known as Bell's inequalities, he showed that, for any local realist formalism, there exist limits on the predicted correlations." However, independent photons or multi-photon states also deliver quantum-strong correlation functions because the Pauli spin operators act on the polarization state regardless of the number of photons it carries. In this context, the overlap, in the measurement Hilbert space, between two polarization Stokes vectors measured separately at two distant locations generate the same correlation functions [8-9], thereby explaining the experimental outcomes without invoking 'quantum nonlocality'.

This article identifies several physical omissions and contradictions which have been overlooked in the literature and which disprove the four aspects or elements of quantum nonlocality: 1. The propagation of single photons in a straight-line inside a dielectric medium is impossible because of the quantum Rayleigh scattering; 2. The wave function collapse involved in the mutual "interaction" leads to a vanishing expectation value for the Pauli operators in the context of a Bell-state, i.e., maximally entangled photons; 3. The strong correlation functions can also be obtained with independent states of photons obviating the need for entangled photons, which leads to last element, that is, 4. Bell-type inequalities are easily violated with unentangled and classical states of polarization [7].

2. The quantum Rayleigh scattering of single photons

Although well-documented, e.g., [13-14], the physical process of quantum Rayleigh scattering has been consistently ignored in the conventional theory of quantum optics [15]. A single photon cannot propagate in a straight-line inside a dielectric medium because of the quantum Rayleigh scattering associated with photon-dipole interactions. Groups of photons are created through parametric amplification in the nonlinear crystal in which spontaneous emissions first occur, generating pair photons from a pump photon. Such a group of photons will maintain a straight line of propagation by recapturing an absorbed photon through stimulated Rayleigh emission. The assumption that spontaneously emitted, parametrically down-converted individual photons cannot be amplified in the originating crystal because of a low level of pump power would, in fact, prevent any sustained emission in the direction of phase-matching condition because of the Rayleigh spontaneous scattering [8-9].

Evidence of single-photon scattering can be found in ref. [12], in the Supplemental Material reporting that "In our experiment no photons are detected during a large number of trials, and these trials contribute little to the Bell violation." Equally, the experiments of [12] "… employed single-photon optical time domain reflectometry (OTDR) to measure the transit time of light through all the optical fibers and some of the free-space optical paths in the experimental setup."

The probability of detecting a photon and its quantum effect is reported in Table S-II on page 16 [12], to be less than 0.01%. This extremely low level of detection probability is also reported in Fig. 3 of ref. [11]. It should be obvious that such extremely low probabilities cannot describe the presence of a physical phenomenon. Rather, these probabilities would indicate random statistical measurements which are consistent with the statistical explanation for measurements of correlated outputs [1-3].

Physically, quantum entanglement of photonic states implies a strong correlation between the same properties of the same variable or degree of freedom measured separately on each of the two entangled photons. These properties are the consequence of a common past interaction between these photons and those properties generated in the common interaction can be carried away from the position and time of that interaction.

3. The absence of quantum nonlocality upon sequential measurements

Quantum nonlocality is claimed to influence the measurement of the polarization state of one photon at location B, which is paired with another photon measured at location A. The two photons are said to be components of the same entangled state. Maximally entangled states, such as $|\psi_{AB}\rangle$ of Eq. (1), represented in the same frame of coordinates of horizontal and vertical polarizations, would deliver the strongest correlation values between separate measurements of polarization states recorded at the two locations A and B.

The experimental results of refs. [11] and [12] were measured with a low level of entanglement, with the reported mixed states having one component much larger than the other, thereby allowing for measurements of unentangled product states. From equations (2) of both references, their experimental optimal ratios of the two amplitudes are 2.9 and 0.961/0.276, respectively [11] and [12].

If a collapse of the wave function is to take place for entangled photons upon detection of a photon at either location, then the two separate measurements do not coincide. In this case, a local measurement vanishes for the maximally entangled Bell states, e. that is, $\langle \psi_{AB} \mid \hat{\sigma}_A \otimes \hat{I}_B \mid \psi_{AB} \rangle = 0$, with $\hat{I}_B = \mid x \rangle\langle x \mid + \mid y \rangle\langle y \mid$ being the identity operator, and the projecting Pauli operators are in this case $\hat{\sigma}_1 = \mid x \rangle\langle y \mid + \mid y \rangle\langle x \mid$ and $\hat{\sigma}_3 = \mid x \rangle\langle x \mid - \mid y \rangle\langle y \mid$. Thus, a physical contradiction arises as local experimental outcomes determine the mixed quantum state of polarization of the ensemble to be compared with its pair quantum state.

This overlooked feature of maximally entangled Bell states renders them incompatible with the polarimetric measurements carried out to determine the state of polarization of photons, thereby explaining the experimental results of ref. [7] which were obtained with independent photons, indicating the possibility of obtaining quantum-strong correlations without entangled photons as pointed out in ref. [9]. The wave function collapse would bring about a product state as part of a time-dependent partial ensemble of measurements.

The mixed quantum state $\mid \psi_{AB} \rangle$ is space- and time-independent and considered to be a global state which can be used in any context, anywhere, and at any time. Nevertheless, the Hilbert spaces of the two photons move away from each other and do not spatially overlap, so that any composite Hilbert space is *mathematically* generated by means of a tensor product at a third location where the comparison of data is performed. Even so, the absence of a Hamiltonian of interaction renders any suggestion of a mutual influence physically impossible [1].

4. Correlation functions

Maximally entangled states, represented in the same frame of coordinates of horizontal and vertical polarizations, would deliver the strongest values of the correlation function

$$E_c = \langle \psi_{AB} \mid \hat{\sigma}_A \otimes \hat{\sigma}_B \mid \psi_{AB} \rangle = cos\ [2\,(\theta_A - \theta_B)] \tag{2}$$

for identical inputs to the two separate apparatuses, with the polarization filters rotated by an angle θ_A *or* θ_B, respectively, from the horizontal axis. However, quantum-strong correlations with independent photons have been demonstrated experimentally [7] but ignored by legacy journals because they did not fit in with the theory of quantum nonlocality. The same correlation function $E_c = cos\ [2\,(\theta_A - \theta_B)]$ is obtained 'classically', as a result of the overlap of two polarization Stokes vectors of the polarization filters on the Poincaré sphere [9] The Stokes parameters correspond to the expectation values of the Pauli spin operators [9].

The correlation function is a *numerical* calculation as opposed to a physical interaction. Thus, the numerical comparison of the data sets is carried out at a third location *C* where the reference system of coordinates is located for comparison or correlation calculations of the two sets of measured data, and does not require physical overlap of the observables whose operators are aligned with the system of coordinates of the measurement Hilbert space onto which the detected state vectors are mapped. In this case, the correlation operator $\hat{C} = \hat{\sigma}_A \otimes \hat{\sigma}_B$ can be reduced to [16; Eq. (A6)]:

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$$\hat{C} = (\boldsymbol{a} \cdot \hat{\sigma})(\boldsymbol{b} \cdot \hat{\sigma}) = \boldsymbol{a} \cdot \boldsymbol{b}\, \hat{I} + i\,(\boldsymbol{a} \times \boldsymbol{b}) \cdot \hat{\sigma} \tag{3}$$

where the polarization vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ identify the orientation of the detecting polarization filters in the Stokes representation, and $\hat{\sigma} = (\hat{\sigma}_1, \hat{\sigma}_2, \hat{\sigma}_3)$ is the Pauli spin vector (with $\hat{\sigma}_2 = i\,\hat{\sigma}_1\,\hat{\sigma}_3$). The presence of the identity operator in Eq. (3) implies that, when the last term vanishes for a linear polarization state, the correlation function is determined by the orientations of the polarization filters. This can be easily done with independent and linearly polarized states, such as:

$$|\,\psi_j\,\rangle = (\,|x\rangle_j + |y\rangle_j\,)/\sqrt{2} \tag{4}$$

where the index *j*= *A* or *B* identifies the photodetector. The same state reaches both detectors.

The polarization operator $\hat{\sigma}$ projects the incoming states onto the measurement Hilbert space for comparison of the two separate data sets. The polarization measurement operators of $\hat{\sigma}(\theta_j) = \sin(2\theta_j)\,\hat{\sigma}_1 + cos(2\theta_j)\,\hat{\sigma}_3$ produce the output states

$$|\Phi_j\rangle = \sin(2\theta_j)\,\hat{\sigma}_1\,|\,\psi_j\,\rangle + cos(2\theta_j)\,\hat{\sigma}_3\,|\,\psi_j\,\rangle \tag{5}$$

which, analogously to the overlapping inner product of two state vectors, lead to the correlation function of

$$E_c = \langle \Phi_A \,|\, \Phi_B \rangle = cos\,2\,(\theta_A - \theta_B) \tag{6}$$

The quantum correlation function of Eq. (6) between two independent states of polarized photons is equivalent to the overlap of their Stokes vectors on the joint Poincaré sphere of the measurement Hilbert space. Quantum-strong correlation are possible with independent states of photons [7] because the source of the correlation is the polarization states of the detecting filters or analyzers, making any claim of quantum nonlocality unnecessary.

5. Bell-type inequalities

Polarimetric measurements made in the quantum regime are based on the Pauli spin operators whose expectation values are displayed on the Poincaré sphere. However, these operators act on the state of polarization regardless of the number of photons carried by the radiation mode, instantaneously. The correlation functions needed to evaluate various Bell-type inequalities take the same form in both the quantum and classical regimes, and correspond to the overlap of the polarization states in the Stokes representation [9].

Quantum measurements violating Bell-type inequalities are supposed to be based on entangled states of single photons and prove the existence of quantum nonlocality. But the violations of inequalities rely on the correlation functions of the two ensembles of measurements as opposed to the same pair of photons, that is, the correlations are obtained as a result of a numerical comparison and are not a physical interaction. The photonic properties were carried away from the space and time of the original interaction, with the *measurement identifying* which of the two photons possessed the respective states of polarization.

Another glaring contradiction of the quantum nonlocality interpretation can be found in ref. [10]. In the caption to Fig.1, on its second page, one reads:

"…if both polarizers area aligned along the same direction (a=b), then the results of A and B will be either (+1; +1) or (-1; -1) but never (+1; -1) or (-1; +1.); this is a total correlation as can be determined by measuring the four rates with the fourfold detection circuit".

This statement first deals with single, individual events but in the second part it mentions "rates" which apply to ensemble of measurements (as degree or comparative extent of action or procedure). Now, if it is possible, with entangled photons, to have 100% correlation at the level of individual events, then one could easily carry out a short series of measurements to find simultaneous detections and prove directly the existence of quantum nonlocality, rather than use, indirectly, Bell-type inequalities to claim it from correlations of ensembles. Ensemble distributions also cover non-simultaneous single detections that are taken to be simultaneous in order to reach the 100% correlation value.

Ensembles of two separate measurements lead to two sets of probabilities. Correlations between distributions of ensemble probabilities are calculated as the expectation value of the correlation operator $\hat{C} = \hat{\sigma}_A \otimes \hat{\sigma}_B$ to be $E_c = cos\ [2\,(\theta_A - \theta_B)]$ as opposed to probabilities of single, individual events $P_{A\ or\ B} = cos^2\theta$, identical for both locations with $E_c = 1$.

For example, if one in ten photons is detected, then, for entangled photons, the two separate detections should happen simultaneously with a ratio of 1:10, as claimed with quantum nonlocality. This would allow a direct measurement and demonstration of quantum nonlocality without the need for Bell-type inequalities that involve ensembles of measurements. But this cannot be done because a single photon is diverted by the quantum Rayleigh scattering in a dielectric medium from a straight-line propagation. Therefore, no quantum nonlocality has been demonstrated in so far as single photons are concerned.

Bell-type inequalities can also be violated classically because the same correlation function is derived for both the quantum and classical regimes, as explained in the previous section 4. Thus, from a technological perspective, functional devices needed for strong correlations between two separate outputs can be achieved with multiple photons, thereby obviating the need for complicated and expensive single photon sources and photodetectors.

6. Conclusions

With a dominant unentangled component and a very low detection probability, the landmark experiments of refs. [11] and [12] prove just the opposite to their claim of definitive evidence of quantum nonlocality. Experimental results and analytic developments published subsequently, rebut the concept of quantum nonlocality whereby a measurement of an entangled photon influences the outcome of a pair-measurement at another location.

Quantum-strong correlations which are needed for quantum data processing, can be produced by means of uncorrelated and multiphoton states as well as 'classically' by means of Stokes parameters on the Poincaré sphere. In this way the complicated and expensive single-photon sources and photodetectors become unnecessary.

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