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Strongly Correlated Detections of Independent Photons Eliminate Entangled Photons

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Abstract
Published experimental results and analytic developments indicate the possibility of achieving stronger correlations of physical events with independent photons rather than with entangled ones. The probability of coincident detections of quantum events should not be confused with the correlation of mixed states. The theoretical requirements for implementing the quantum nonlocality theory are not present in the experimental configurations purporting to prove Bohr's or Bell's nonlocality because of the quantum Rayleigh scattering of single photons. By means of a normalization factor corresponding to the total number of initiated events, the detection probabilities obtained experimentally are too small to enable any violation of a Bell inequality. Correlations between independent states of qubits can easily outperform those calculated with entangled photons. Additionally, the quantum joint probability for a Bell state can be factorized enabling a local detection of the alleged quantum nonlocality, if it existed.

Keywords: Quantum Rayleigh Scattering, Quantum Correlations, Independent Photons

1. Introduction

In a recent spotlight article in Nature, the following paragraph can be found: "In fact, all quantum computers could be described as terrible [1]. Decades of research have yet to yield a machine that can kick off the promised revolution in computing". This is not surprising in light of many and varied physical contradictions and inconsistencies which are outlined in this article identifying physical processes hindering the implementation of the mathematical formalism of quantum non-locality in the context of photonic systems, as well as outlining feasible methods for the manipulation of state vectors on the Poincaré sphere for qubit data processing.

Over the last four decades or so, a narrative has been gradually entrenched in the field of quantum physics stating that the quantum environment of very low levels of energy associated with single photons, features a remarkable property of contact-free, remote influence by one act of detection or measurement on a second measurement of the other entangled pair-photon [2-4]. The resultant correlations are meant to constitute a fundamental resource in quantum computing, and would require single-photon sources and photodetectors. Nevertheless, experimental results and analytic developments have identified the possibility of achieving quantum-strong correlations with independent and multi-photon states [5-8].

A basic principle of scientific methodology is the reproducibility of experimental results, namely, identical physical systems operated under identical conditions will yield identical distributions of measured outcomes. This principle of scientific research has been ignored when dealing with quantum correlations between separate measurements which have been touted as a technological resource for the practical implementation of quantum computers [2-4]. The benchmark for quantum correlations takes the form of Bell-inequalities which should be violated only by quantum probabilities calculated as the expectation values of a product of operators in the context of wavefunctions describing, in our case, polarization- entangled single photons.

The effect of quantum nonlocality is meant to synchronize the detections recorded at the two locations A and B for polarization-entangled states of photons. In the caption to Figure 1 of ref 9, on its second page, one reads: "…if both polarizers are 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 [9]". Yet, the quantum correlation is supposed to take place at the level of each pair of entangled photons rather than between averaged values of the two distributions; but such an outcome has never been reported. The maximal, experimentally measured probability of coincident counts reported in the landmark experiments of refs 10, 11 is $2x10^{-4}$ (or 0.0002) which was achieved with highly non-entangled states and is indicative of the non-existence of the mythical Bohr's nonlocality [10,11].

Additionally, the Bell parameter $S = \langle a_0\ b_0\rangle + \langle a_0\ b_1\rangle + \langle a_1\ b_0\rangle - \langle a_1\ b_1\rangle$ of eq. (4) in [3] would actually vanish as $\langle a_1\ b_1\rangle=\langle a_0\ b_0\rangle=-1$ and $\langle a_1\ b_0\rangle=\langle a_0\ b_1\rangle=0$ according to the expectation values [3, p. 422] of $\langle a_x\ b_y\rangle = -\vec{x}\cdot\vec{y}$, for detection settings $\vec{x}_{0;1} \| \vec{y}_{0;1}$, and $\vec{x}_{0;1} \perp \vec{y}_{1;0}$ of the polarization states for coincident detections. Thus, S=0, failing to violate the CSHS inequality despite involving the strongest quantum correlations. This fact should have rung alarm bells about the irrelevance of the Bell-type inequalities as an indicator of strong correlations between the same order elements of two sequences. This shortcoming will be elaborated upon in this article.

However, from an experimental perspective, the correlation probability of simultaneous detections $p_c(a,b)$ is evaluated from a third sequential distribution $v_c(a;b)$ calculated as the temporal vector or dot product of the two initial sequences $v(a,x)=\{a_m\}$ and $v(b,y)=\{b_m\}$ leading to $p_c(a,b)=(\Sigma_{m=1}^{N} a_m b_m)/N$ where $a,b=0$ or 1 are assigned binary values for no-detection or detection of an event, respectively. For any ensemble of measurements, the values of the correlation or joint probability $p_c(a,b)$ will depend on the sequential orders of the two separate ensembles at locations A and B. Therefore, as the quantum formalism does not provide any information about those sequential orders, any artificial boundary such as Bell-inequalities are physically meaningless, because for the same values of the local probabilities, $p_A(a)$ and $p_B(b)$, the higher values of $p_c(a,b)$ will lead to a violation of the Bell inequality in the classical regime. Bell inequalities can be easily violated with independent photons [5-7].

Equally, the experimental results of ref. [4] alleging propagation of single photons through the atmosphere over a distance of more than 100 km are physically impossible because of the quantum Rayleigh scattering [12] of single photons which will prevent synchronized detections. A physically meaningful explanation was presented in refs. [13-14] and can be summarized as follows. The spontaneously emitted photons in the nonlinear crystal undergo parametric amplification forming a group of identical photons. This group of photons can overcome the quantum Rayleigh scattering through quantum Rayleigh stimulated emission. This is illustrated in Figure 1 and detailed in refs. [13-14].

Additionally, a sub-section of ref. [3] headlined "More nonlocality with less entanglement" leads one to the anomaly of nonlocality. "Astonishingly, it turns out that in certain cases, and depending on which measure of nonlocality is adopted, less entanglement can lead to more nonlocality." [3, p.442]. "Remarkably, it turns out that this threshold efficiency can be lowered by considering partially entangled states. ….This astonishing result was the first demonstration that sometimes less entanglement leads to more nonlocality " [3, p. 464].

"Since it is expressed in terms of the probabilities for the possible measurement outcomes in an experiment, a Bell inequality is formally a constraint on the expected or average behavior of a local model. In an actual experimental test, however, the Bell expression is estimated only from a finite set of data and one must take into account the possibility of statistical deviations from the average behaviour" [3, p. 466]. For a distinction between probability and frequency of occurrence, the reader is directed to ref. [15]

It is claimed that "…quantum correlations cannot be reproduced using no-signalling theories which make more accurate predictions of individual properties compared to quantum theory [3, p. 469]". Equally, "Quantum correlation is a fundamental aspect of quantum mechanics and serves as the crucial link between quantum and classical physics. When quantum correlations between subsystems for a system reach a certain threshold, the system is entangled, which has diverse applications in quantum information processing". Nevertheless, experimental results of quantum-strong correlations have been achieved with independent, non-entangled photons [5,6].

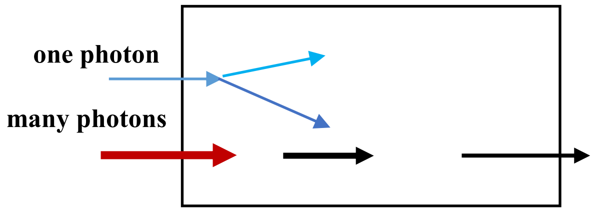

Figure 1: Schematic of one photon being randomly scattered inside a dielectric medium, while a group of identical photons propagates in a Straight-line [9].

These statements will be disproved in Section 1.1 by identifying physical probabilities evaluated with independent photons that outperform the quantum correlations based on entangled photons. Correlations of coincident detections of independent photons are derived in Section 2, while control of such correlations is presented in Section 3. The complete derivation of the quantum joint probability in the context of the collapse upon a first measurement of the entangled state of photons is presented in Section 4 leading to a factorization of local probabilities, thereby enabling a local test of the quantum nonlocality without the need for an arbitrary Bell inequality. Further contradictions and omissions are listed in Section 5.

2. Probabilities of Detecting Independent Photons Exceeding Those of Entangled Photons

2.1. Normalization with the Number of Initiated Events

The quantum correlation function $E_c(1;1|\alpha;\beta)$ for detecting one photon at location A and its pair-photon at location B, is defined in terms of four probabilities between two orthonormal detection-settings at each of the two locations A and B, for eigenvalues +1 or−1, respectively, of local settings α or α', and β or β' leading to the linear combination of probabilities P_{ij} [2], [4]:

$$E_c(1;1|\alpha;\beta) = P_{++}(\alpha;\beta) + P_{--}(\alpha';\beta') -$$
$$-P_{+-}(\alpha;\beta') - P_{-+}(\alpha';\beta) \quad (1)$$

where $\alpha'=\alpha+\pi/2$ and $\beta'=\beta+\pi/2$. Fluctuations in the number of detections would give rise to a spread in the values of P_{ij} and $E_c(1;1|\alpha;\beta)$. This correlation function is normally linked to the polarimetric Stokes measurements or the quantum Pauli vector operators and has the same form in both the quantum and classical regimes [7], so that its use in the Clauser-Horne-Shimony-Holt (CHSH) inequality cannot discriminate between quantum and classical outcomes.

For the CHSH inequality [4], the correlation probability is $P_{++}(\alpha;\beta)=N_{++}(\alpha;\beta)/N_{norm}$ where N_{++} is the number of coincident counts of photons and N_{norm} is the number of all coincident detections for all four settings $N_{norm} = N_{++}(\alpha;\beta) + N_{--}(\alpha';\beta') + N_{+-}(\alpha;\beta') + N_{-+}(\alpha';\beta)$.

However, this normalization is mathematical because the physical number $N_{norm}=N_{in}$ of initiated photon-pairs is very much larger as photons are lost between the source and the photodetectors, for various reasons, thereby throwing doubt about the real statistics. This normalization makes a violation of the CHSC impossible as $N_{++}/N_{in} \ll 0.1$.

The Clauser-Horne (CH) inequality has arbitrary values for the two measurement settings, i.e., α *and* α' as well as β *and* β' are set separately. The CH inequality also contains correlations between '1's and '0's, so that, in terms of binary-valued probabilities $p(1,1;\alpha,\beta)$ and similar forms, [10-11], the inequality is written as:

$$p\,(1,1;\alpha,\beta) - p\,(1,1;\alpha',\beta') \leq$$
$$\leq p\,(1,0;\alpha,\beta') + p\,(0,1;\alpha',\beta) \quad (2)$$

with the normalization factor N_{in} of initiated events being used. But, as only one term of the four terms is measured in any given run, the linear combination would relate the maximal values on the left-hand side to the minimal values on the right-hand side. With such probabilities for all four terms, the opposite requirements of the inequality for the coincident detections of (1;1) on the left-hand side, and for only one-location detection (1;0) or (0;1) on the right-hand side, make a violation impossible, mathematically, unless arbitrary values are selected from various data sets. In this case, the inequality becomes physically meaningless.

For an input of multi-photon states, loss effects may not annihilate all the input photons, so that the number of detections increases regardless of the projective probability $p(\alpha)=cos^2\alpha$ which provides a mathematical average. For a single-photon input, the density distribution per solid angle $\Delta\Omega$ of the mixed quantum state arising from spontaneous emission that follows the radiation pattern of an oscillating dipole is [16-17]:

$$p(\theta)\Delta\Omega = \frac{cos^2\,\theta\,\Delta\theta\,\Delta\varphi}{2\pi\int_{-\pi}^{\pi} cos^2\,\theta\;d\theta} \quad (3)$$

where the solid angle of emission is $\Delta\Omega$, the polar angle between the electric dipole vector and the polarization vector of the emitted photon is θ, and φ is the azimuthal angle in the plane perpendicular to the dipole [16-17]. It is this distribution of the Rayleigh spontaneously emitted photons over the range $\{-\pi,\pi\}$, that randomly rotates the polarization state of the absorbed photons.

Physically, however, one single photon is scattered randomly by quantum Rayleigh photon-dipole interactions. By contrast, a group of identical photons can propagate in a straight line inside a dielectric medium through quantum Rayleigh stimulated emission. This process of stimulated emission can also amplify a spontaneously emitted photon with a rotated polarization, particularly so if the polarization modulator and analyser enable a lossless mode to propagate [13-14].

2.2. Linking Projective Measurements to the Theoretical Correlation Function

Quantum correlations are evaluated as the expectation values of a product of operators [2-3]. For the projective operators $\widehat{\Pi}(\alpha)=|H_\alpha\rangle\langle H_\alpha|$ *and* $\widehat{\Pi}(\beta)=|H_\beta\rangle\langle H_\beta|$ corresponding to the polarization filters with one detection setting at each of the two locations A and B, respectively, the probability of coincident detections has the form, cf. [3, eq. 13]:

$$p\,(1,1;\alpha,\beta) = \left|(\langle\psi_{in}|\widehat{\Pi}(\alpha))\;(\widehat{\Pi}(\beta)\;|\psi_{in}\rangle)\right|$$
$$= \left|\langle\Phi_\alpha|\Phi_\beta\rangle\right| \quad (4)$$

with $|H_\alpha\rangle$ and $|H_\beta\rangle$ identifying the states of the polarization filters, and $\langle\Phi_\alpha|=\langle\psi_{in}|\widehat{\Pi}(\alpha)$ for the Hermitian conjugate state. For the polarization-entangled photons, the outcomes consist of the overlap between two state vectors rotated on the Poincaré sphere and are defined as the correlation function $C(\alpha;\beta)$ between two (mixed) states; by contrast, experimentally, the probability of coincident detections is calculated from the sum of products of overlapping terms, i.e., $p_c(a,b)=(\Sigma_{m=1}^{N} a_m\, b_m)/N$, as defined in the Introduction, and identifies the fraction of simultaneous detections at the level of each quantum event. This discrepancy is part of the disconnect between theory and measurement.

For the basis states $|H\rangle$ *and* $|V\rangle$ of the shared measurement Hilbert space, the projective amplitudes are $\langle H_\alpha|H_A\rangle=cos\alpha$, $\langle H_\alpha|V_A\rangle=sin\alpha$, $\langle H_\beta|H_B\rangle=cos\beta$ and $\langle H_\beta|V_B\rangle=sin\beta$. The correlation function $C(\alpha;\beta)$ of magnitude $|C(\alpha;\beta)|= p\,(1,1;\alpha,\beta)$ between filter polarization states and for independent states of photons $|\psi_{in}\rangle$ becomes:

$$C(\alpha;\beta) = \langle\Phi_\alpha|\Phi_\beta\rangle = \langle\psi_{in}|H_\alpha\rangle\,\langle H_\alpha|H_\beta\rangle\langle H_\beta|\psi_{in}\rangle \quad (5a)$$

$$|\psi_{in}\rangle = (\,|H\rangle\; + \;|V\rangle\,)/\sqrt{2} \quad (5b)$$

$$|H_\alpha\rangle = \cos\alpha\,|H\rangle + \sin\alpha\;|V\rangle;\; |H_\beta\rangle = \cos\beta\,|H\rangle + \sin\beta\;|V\rangle \quad (5c)$$

$$C(\alpha;\beta) = 0.5[cos\,\alpha + \sin\alpha]\;[cos(\alpha-\beta)]\;\times$$
$$\times\;[cos\,\beta +\; sin\,\beta] =$$
$$=\;0.5\cos(\alpha-\beta)[\cos(\alpha-\beta) + \sin(\alpha+\beta)] \quad (5d)$$

This correlation of eq. (5d) is composed of three terms indicated in the first equality. The projections of the input states onto the respective filters are given by the sum of the sine and cosine functions, while the term $cos(\alpha-\beta)$ indicates the overlap between the two filters. The magnitude of this correlation function or probability of coincident detections can reach a peak of unity for the symmetric case of $\alpha=\beta=\pi/4$ *or* $\pi/4\pm\pi$, outperforming the coincidence values of 0.5 obtained with entangled states of photons as presented in Section 5.

3. Correlated or Coincident Detections of Independent Photons

A series or an ensemble of detection measurements is mathematically cast into a temporal vector $v(\alpha,\theta_A)$ along polarization output angle θ_A, and for a polarization input setting α. The elements of the data vector are c_m=1 *or* 0 for a detection event or no detection, respectively, of the *m*-th order element. Thus, $v(\alpha,\theta_A)$ has the following averaged number of '1' terms summed over the probing times $\delta(t-t_m)$, for one photon of polarization *H* or *V* in the measurement frame of coordinates:

$$\overline{v}\,(\alpha;\theta_A)=\frac{1}{N}\sum_{m=1}^{N_H} c_{m;H}(\alpha,\theta_A)\ \delta\left(t-t_{m;H}(\alpha,\theta_A)\right)$$

$$+\frac{1}{N}\sum_{m=1}^{N_V} c_{m;V}(\alpha,\theta_A)\ \delta\left(t-t_{m;V}(\alpha,\theta_A)\right)=$$

$$=\ P_H(\alpha,\theta_A)+\ P_V(\alpha,\theta_A)=$$

$$=\ 0.5\,\eta\,[cos^2\ (\theta_A-\alpha)+sin^2\ (\theta_A-\alpha)]=\frac{1}{2}\,\eta \quad (6)$$

where η specifies the quantum efficiency of cross-polarization coupling, $N_H=N_V=N/2$, namely, the total number of events *N* is split equally between the two input polarizations *H* or *V* polarization, θ_A is the polarization angle of the analysing filter at location A, α is a rotation setting of the electro-optic modulator, the probing times are $t_{m;H}(\alpha)\neq t_{m;V}(\alpha)$ and $P_{H;V}(\alpha,\theta_A)$ is the probability of detecting a pulse, for input *H* or *V* and polarization filter rotated by α. For input polarization *V*, orthogonal to *H*, the rotation angle is: $\pi/2-\alpha$ and the probability of detection along θ_A is $P_V(\alpha,\theta_A)=sin2\ (\theta_A-\alpha)$. The average number of '0's is found from the expression: $\overline{v}_0\ (\alpha,\theta_A)=1-\overline{v}_1\ (\alpha,\theta_A)$.

The correlation vector $v_C(\alpha;\beta)$ of simultaneous detections between two arbitrary and random series $v(\alpha)$ and $v(\beta)$ or ensembles, at locations A and B, respectively, is expressed as the product of the two m-th order terms, of simultaneous or coincident detections $v_C(\alpha;\beta)=v(\alpha)\cdot v(\beta)$ leading to an average $\overline{v_C(\alpha;\beta)}$ of '1's or joint probability of simultaneous detections:

$$\overline{v_C(\alpha;\beta)}=\overline{v(\alpha)\cdot\ v(\beta)}\Rightarrow P(\alpha;\beta)$$

$$P(\alpha;\beta)=\frac{1}{N}\sum_{m=1}^{N} c_m(\alpha)\ c_m(\beta) \quad (7)$$

By considering all possible combinations in Eq. (7), it is obvious that the order of the random distributions of the two sequences will determine the value of the joint probability of correlation $P(\alpha;\beta)$ whose maximal value equals the lowest of the two local probabilities $P(\alpha)$ *and* $P(\beta)$. The values of $P(\alpha;\beta)$ may exceed the *definition* of the local condition for independent probabilities [2-3], i.e., $P(\alpha;\beta)=P(\alpha)\ P(\beta)$. These analytic results modelling lossless systems would produce, as explained in the Introduction, correlation values larger than 0.25 which cannot be achieved experimentally because of the presence of the quantum Rayleigh scattering of photons [12].

A distinction needs to be made between the probability of coincident events at the level of each individual event, and the product of probabilities of '1's in each ensemble of measurements which is, in fact, the product of the averaged values of polarization states.

From a physical perspective, identical systems operated in identical ways will yield identical distributions of outcomes, which is critical in the reproduction of experimental results. Given the low quantum efficiencies of 'single-photon' detections, the performance of correlated outputs can be significantly increased by launching, into the two systems, groups of identical photons as generated by the parametric amplification in the original crystal [13-14], or externally controlled number of photons [5-6]. In such circumstances, the likelihood of a few photons reaching the output photodetectors simultaneously will be even larger than the probability of Eq. (6).

4. Polarization-Controlled Output of Multi-Photon States

With multiple photons propagating in both input orthogonal states of polarization *H* and *V*, one can control the output intensity through interference of the intrinsic fields [14] of groups of identical photons coupled onto the filter's polarization state of rotation angle θ_A. Following the results of [13-14] that identified dynamic and coherent number states $|\Psi_n(\omega,t)\rangle=(|n(t)\rangle+|n(t)-1\rangle)/\sqrt{2}$ and recalling the non-Hermicity of the field operators [14], we find that $\hat{a}\ |n\rangle=\sqrt{n\ e^{-i\varphi}}|n-1\rangle$, which provides a complex field amplitude [14], for the time-dependent evolutions of photonic beam fronts. The output intensity, for fluctuating numbers of photons $N_{ph}(\theta_A,t)$ and the expectation number $\langle N_{ph}(\theta_A,t)\rangle$ of the interference between pure states, take the forms:

$$N_{ph}(\theta_A,t)=\eta\ 0.5[\ N_H(t)\ cos^2(\theta_A)+\ N_V(t)\ sin^2(\theta_A)+$$

$$+2\ \Gamma(\tau)\sqrt{N_H(t)N_V(t)}\,sin\ (\theta_A)\ cos(\ \theta_A)\ cos\left(\xi_H(t)-\xi_V(t)\right)] \quad (8)$$

$$\langle N_{ph}(\theta_A,t)\rangle=\eta\ 0.5\ \langle\ N_{tot}(t)\ \times$$

$$\times\,[1+\ \sigma(t,\ \theta_A)\ \Gamma(\tau)\ cos(\xi_H(t)-\xi_V(t))]\ \rangle \quad (9)$$

where $\sigma(t,\theta_A)=sin\ (2\,\theta_A)\sqrt{N_H(t)\ N_V(t)}/\ N_{tot}(t)$ is the visibility with $N_{tot}(t)=N_H(t)\ cos^2(\theta_A)+N_V(t)\ sin^2(\theta_A)$, and $\Gamma(\tau)$ is the temporal overlap between the intrinsic optical fields of the photons whose derivation is available in [14]. The time-varying phases of the two polarization states are ξ_H *and* ξ_V, and the time-average is indicated by the angled brackets.

By varying parameters in eq. (9), the lowest number of photons is always larger than zero, which increases the probability of detection. Overall, the more photons are trapped in the system through quantum Rayleigh spontaneous emission [13-14], the more likely it is for groups of identical photons to form through quantum Rayleigh stimulated emission [14]. As a result, single photons coalesce into groups of multi-photon states, thereby changing the statistical outcomes.

5. The Wave Function Collapse Leading to Factorization of the Quantum Joint Probability

A rigorous derivation based on the formalism of wave function collapse of a maximally entangled state will provide a method to test the concept of quantum nonlocality. If no detection takes place at location A, the projective measurement at location B involves the operator $\widehat{\Pi}\ (\beta)=|H_\beta\rangle\ \langle H_\beta|$ acting on the initial state

$$|\psi_{AB}\rangle = (\ |H_A\rangle\ |V_B\rangle -\ |V_A\rangle\ |H_B\rangle)/\sqrt{2} \tag{10}$$

and resulting in the probability of detection

$$P_\beta = \langle\psi_{AB}|\hat{I}_A \otimes |H_\beta\rangle\ \langle H_\beta| \otimes\ \hat{I}_A|\psi_{AB}\rangle = (cos^2\beta + sin^2\beta)/2 = 1/2 \tag{11}$$

after setting $\langle H_\beta|H_B\rangle = cos\beta$ and $\langle H_\beta|V_B\rangle = sin\beta$ for the projective amplitudes onto the polarization filter. Similarly, for the first detection at location A, i.e., $P_\alpha = 1/2$.

If a first detection takes place at location A involving the projective operator $\hat{\Pi}(\alpha)=|H_\alpha\rangle\ \langle H_\alpha|$, it will result in an intermediary state for the projective amplitudes $\langle H_\alpha|H_A\rangle = cos\alpha$ and $\langle H_\alpha|V_A\rangle = sin\alpha$, so that the reduced or collapsed wave function $|\psi_B|A\rangle$ becomes:

$$|\psi_{B|A}\rangle = |H_\alpha\rangle\ \langle H_\alpha| \otimes\ \hat{I}_B|\psi_{AB}\rangle = \\ = \frac{1}{\sqrt{2}}\ (cos\ \alpha\ \ |V_B\rangle - sin\ \alpha\ \ |H_B\rangle)\ |H_\alpha\rangle \tag{12}$$

$$|\psi_B\rangle = \frac{|\psi_{B|A}\rangle}{\sqrt{\mathbb{N}}} = \frac{|H_\alpha\rangle\langle H_\alpha| \otimes\ \hat{I}_B|\ \psi_{AB}\rangle}{\sqrt{\mathbb{N}}} \tag{13}$$

where $|\psi_B\rangle$ denotes the normalised wave function for the calculation of the detection probability at location B, conditional on a detection at location A. The normalization factor $\mathbb{N}=1/2$ for the collapsed wave function $|\psi_B|A\rangle$ corresponds to the probability of detection P_α for the first measurement, and after substituting for $|\psi_B\rangle$ from eq. (13) we have:

$$P_\alpha = \langle\psi_{AB}|\hat{I}_B \otimes |H_\alpha\rangle\langle H_\alpha| \otimes\ \hat{I}_B|\psi_{AB}\rangle = |\langle H_\alpha|\psi_{AB}\rangle|^2 = \\ = \mathbb{N}\ \langle\psi_B|\psi_B\rangle = 1/2 \tag{14}$$

Based on the normalized state $|\psi_B\rangle$, the probability of detection at location B following a detection at location A, becomes in this case, for a projective measurement:

$$P_{\beta|\alpha} = \langle\psi_B|H_\beta\rangle\ \langle H_\beta|\psi_B\rangle = |\ cos\ \alpha\ \ sin\ \beta - sin\ \alpha\ cos\ \beta|^2 \\ = sin^2(\beta - \alpha) \tag{15}$$

This result which can be found in [2, Sec.19.5] implies that for $\beta-\alpha=\pm\pi/2$, regardless of the values of $\beta\ or\ \alpha$, the local probability of detection at location B could peak at unity even though the probability at location A is limited to 1/2. This theoretical outcome is easily testable experimentally for direct evidence of a quantum nonlocal effect influencing the second measurement after the wave function collapse. But this has never been done either because of the quantum Rayleigh scattering [12] of a single-photon and/or the non-existence of such a nonlocal effect. The product of the local probabilities of eqs. (14) and (15) equals the expression of the joint probability $P_{\alpha\beta}$ for simultaneous detections at both locations A and B, that is:

$$P_{\alpha\beta} = \left|\langle H_\beta|\langle H_\alpha|\frac{|\psi_{AB}\rangle}{\sqrt{P_\alpha}}\right|^2 P_\alpha\ =\ \left|\langle H_\beta|\psi_B\rangle\right|^2 P_\alpha = P_{\beta|\alpha}\, P_\alpha \tag{16a}$$

$$P_{\alpha\beta} = \langle\psi_{AB}|H_\alpha\rangle|H_\beta\rangle \otimes \langle H_\beta|\langle H_\alpha|\psi_{AB}\rangle = 0.5\ \ sin^2(\beta - \alpha) \tag{16b}$$

$$P_{\alpha\beta} =\ P_\alpha\, P_{\beta|\alpha}\ \le P_\alpha\, P_\beta \tag{16c}$$

after inserting from Eqs. (13-15) in the equality (16a). The equality (16b) provides a direct calculation of the joint probability, confirming the validity of the derivation. With the conditional probability of local detection $P_{\beta|\alpha}$ being, mathematically, lower than, or at best, equal to the local probability of detection P_β in the absence of a first detection, i.e., $P_{\beta|\alpha} \le P_\beta$, the formalism of wave function collapse gives rise to a factorization of local probabilities and imposes an upper bound on the quantum joint probability, in clear contradiction to the conventional assumption [2, p.538], [3]. This formalism delivers average values of the ensembles rather than correlation between the sequential orders of the detections. The possibility of factorizing the quantum probability for joint events as in (16a) is identical to the classical case of joint probabilities with the second local probability being conditioned on a first detection. This strong similarity between the classical and quantum joint probabilities renders the local condition of separability [2], [3] irrelevant for the derivation of Bell inequalities.

6. The Flaws of the Quantum Nonlocality Interpretation of Experiments

For the two polarized photons shown in the inset to Figure 1 of ref. [9] "quantum mechanics predicts that the polarization measurements performed at the two distant stations will be strongly correlated [9]." Yet, quantum-strong correlations can also be achieved with independent photons or classical systems [5-7]. Another quotation of interest from 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 [9]." Once again, as pointed out above, Bell inequalities can be violated with expectation values from independent and multi-photon states [5-7].

At least three critical elements have been ignored in the interpretations of experimental results alleging proof of quantum nonlocality: 1) the quantum Rayleigh scattering involving photon-dipole interactions in a dielectric medium, which prevents a single photon from propagating in a straight-line, thereby obstructing the synchronized detections of initially paired-photons; 2) the unavoidable parametric amplification of the spontaneously emitted photons in the nonlinear crystal of the original source and 3) the experimental evidence of quantum-strong correlations between polarization states or statistical ensembles of multi-photon, independent states [5,6,8,12-14].

Maximally entangled states $|\psi_{AB}\rangle$, represented in the same frame of coordinates of horizontal and vertical polarizations, would deliver, allegedly, the strongest values of the correlation function E_c for the Pauli spin vectors operators $\hat{\sigma}_A$ and $\hat{\sigma}_B$, e.g., $E_c = \langle\psi_{AB} | \hat{\sigma}_A \otimes \hat{\sigma}_B |\psi_{AB}\rangle = cos\,[2\,(\theta_A - \theta_B)]$ 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 [5] but ignored by legacy journals because they did not fit in with the theory of quantum nonlocality. The same correlation function is obtained 'classically', as a result of the overlap of two polarization Stokes vectors of the polarization filters on the Poincaré sphere [7]. The Stokes parameters correspond to the expectation values of the Pauli spin operators [7].

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 [18; Eq. (A6)]:

$$\hat{C} = (\boldsymbol{a} \cdot \hat{\sigma})(\boldsymbol{b} \cdot \hat{\sigma}) = \boldsymbol{a} \cdot \boldsymbol{b}\, \hat{I} + i\,(\boldsymbol{a} \times \boldsymbol{b}) \cdot \hat{\sigma} \qquad (17)$$

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. (17) implies that, when the last term vanishes for a linear polarization state, the correlation function is determined by the orientations of the polarization filters.

The theoretical concept of photonic quantum nonlocality cannot be implemented physically because of the quantum Rayleigh scattering of single photons [12]. Landmark experiments [10-11] 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 0.001, the alleged quantum nonlocality cannot be classified as a resource for developing quantum computing devices, despite recent publicity.

All the experimental evidence indicates the absence of a quantum effect between two simultaneously measured single and entangled photons because of the quantum Rayleigh scattering of single photons. The theoretical quantum joint probability for entangled photons is limited by an upper value of 0.5, whereas the correlation between independent qubits on the Poincaré sphere can exceed 0.5 as shown in Section 2. Equally, the classical correlation coefficient between two sequences of arbitrarily distributed binary values can be larger than 0.5, calculated as the sum of same order, overlapping, product components of '1' or '0'.

The quantum reality of independent states of photons takes precedence over the quantum nonlocality of statistically mixed quantum states by delivering stronger quantum correlations as explained in Section 2. The mixed states are time- and space independent and can be used at anytime, anywhere and in any context regardless of the physical context and circumstances. Thus, discarding critically informative aspects of the photonic systems being probed leads to the need for 'counter-intuitive' explanations such as the quantum nonlocality phenomenon.

Consequently, the physical reality as promoted by Einstein prevails over the mythical quantum nonlocality of Bohr, if only because a single photon will be scattered about in a dielectric medium by the quantum Rayleigh scattering.

7. Conclusion

The search for single-photon sources and photo-detectors is rather unnecessary because groups of identical photons perform equally well in terms of correlations of coincident measurements required for data processing with independent polarization qubits. A long series of physical errors, some of which stemming from disregard for scientific methodology, have been covered up over the last six decades. An arbitrarily defined probability threshold which, allegedly, can only be violated by quantum correlations was repeatedly proven to be physically incorrect. Experimental outcomes purporting to prove the role of polarization-entangled photons were, in fact, modelled with a high level of non-entangled states. The formalism of the wave function collapse of the entangled states, when fully analysed, leads to the factorization of the quantum probability of joint detections, thereby enabling a local verification of the claimed quantum nonlocality, if it existed.

No explanation is provided in ref 19 about the physically meaningful process of Rayleigh scattering of single photons which prevents synchronized detections of the original pair of entangled photons [19]. The absence of such experimental evidence is consistent with the analysis based on the concept of wave function collapse leading to the factorization of the quantum joint probability. This, in turn, should enable a local determination of the alleged quantum nonlocality, which has never been done. Therefore, Gisin's statement that "…a violation of a Bell inequality proves that no future theory can satisfy the locality condition" is physically unsubstantiated given the evidence to the contrary presented in Sections 2 and 3 above, and references [5,6].

The intrinsic and monochromatic field of photons has the same localized spatial profile and fall-off regardless of the source of origin [14]. In a dielectric medium, e. g., a cubic beam splitter, saturated with input single photons scattered through quantum Rayleigh spontaneous emission, groups of identical photons will form through quantum Rayleigh stimulated emission [13,14]. The combination of amplified spontaneous emission and its random phase will provide physically meaningful explanations for the Hong-Ou-Mandel effect of vanishing correlations [20] between separate photodetectors, which is used experimentally to confirm the quality of indistinguishable single photons [13,14]. The concept of quantum interference of probability amplitudes resulting from a lack of knowledge associated with probabilities of alternative (which-way) propagation pathways is time-independent and as such can be easily reproduced with multi-photon states populating the pathways simultaneously as a result of amplified spontaneous emission [13,14]. All the examples presented in ref can be explained in terms of simultaneous multi-photon interference of dynamic and coherent number states that deliver phase-related interference with fluctuations of number of photons, analogously to wave interference [13,14].

References

1. Brooks, M. (2023). The race to find quantum computing's soft spot. *Nature, 617*, S1-S3.
2. Garrison, J., & Chiao, R. (2008). *Quantum optics*. OUP Oxford.
3. Brunner, N., Cavalcanti, D., Pironio, S., Scarani, V., & Wehner, S. (2014). Bell nonlocality. *Reviews of Modern physics, 86*(2), 419.
4. Ursin, R., Tiefenbacher, F., Schmitt-Manderbach, T., Weier, H., Scheidl, T., Lindenthal, M., ... & Zeilinger, A. (2007). Entanglement-based quantum communication over 144 km. *Nature physics, 3*(7), 481-486.
5. Iannuzzi, M., Francini, R., Messi, R., & Moricciani, D. (2020). Bell-type polarization experiment with pairs of uncorrelated optical photons. *Physics Letters A, 384*(9), 126200.
6. Ivashkin, A., Abdurashitov, D., Baranov, A., Guber, F., Morozov, S., Musin, S., ... & Tkachev, I. (2023). Testing entanglement of annihilation photons. *Scientific Reports, 13*(1), 7559.
7. Vatarescu, A. (2022). Polarimetric quantum-strong correlations with independent photons on the Poincaré sphere. *Quantum Beam Science, 6*(4), 32.
8. Vatarescu, A. (2019, August). The Scattering and Disappearance of Entangled Photons in a Homogeneous Dielectric Medium. In Conference on Coherence and Quantum Optics (pp. M5A-19). Optica Publishing Group.
9. Aspect, A. (2015). Closing the door on Einstein and Bohr's quantum debate. *Physics, 8,* 123.
10. Giustina, M., Versteegh, M. A., Wengerowsky, S., Handsteiner, J., Hochrainer, A., Phelan, K., ... & Zeilinger, A. (2015). Significant-loophole-free test of Bell's theorem with entangled photons. *Physical review letters, 115*(25), 250401.
11. Shalm, L. K., Meyer-Scott, E., Christensen, B. G., Bierhorst, P., Wayne, M. A., Stevens, M. J., ... & Nam, S. W. (2015). Strong loophole-free test of local realism. *Physical review letters, 115*(25), 250402.
12. Vinogradov, A. P., Shishkov, V. Y., Doronin, I. V., Andrianov, E. S., Pukhov, A. A., & Lisyansky, A. A. (2021). Quantum theory of Rayleigh scattering. *Optics Express, 29*(2), 2501-2520.
13. Vatarescu, A. (2023). The Quantum Regime Operation of Beam Splitters and Interference Filters. *Quantum Beam Science, 7*(2), 11.
14. Vatarescu, A. (2022). Instantaneous quantum description of photonic wavefronts and applications. *Quantum Beam Science, 6*(4), 29.
15. Tipler, F. J. (2014). Quantum nonlocality does not exist. *Proceedings of the National Academy of Sciences, 111*(31), 11281-11286.
16. Louisell, W. H. (1973). Quantum statistical properties of radiation. New York and London: John Wiley.
17. Marcuse, D. (1980). Principles of Quantum Electronics Academic. New Jersey.
18. Gordon, J. P., & Kogelnik, H. (2000). PMD fundamentals: Polarization mode dispersion in optical fibers. *Proceedings of the National Academy of Sciences, 97*(9), 4541-4550.
19. Gisin, N. (2023). Quantum non-locality: from denigration to the Nobel Prize, via quantum cryptography. *Europhysics News, 54*(1), 20-23.
20. Mandel, L. (1999). Quantum effects in one-photon and two-photon interference. *Reviews of Modern Physics, 7*1(2), S274-S282.