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Einstein's Reality Prevails over Bohr's Nonlocality—Stronger Quantum Correlations with Independent Photons Disprove Quantum Nonlocality

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Abstract: Maximal quantum correlations of unity do not violate the CSHS-Bell inequalities because the remaining two correlations vanish. The probability of coincident detections 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

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1. Introduction

Quantum correlations between separate measurements [1,2] have been touted as a technological resource for the practical implementation of quantum computers. 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 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 [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." 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. [3,4] is $2\text{x}10^{-4}$ (or 0.0002) which was achieved with highly non-entangled states and is indicative of the non-existence of the mythical Bohr's nonlocality.

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 [2] 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 [2, p. 422] of $\langle a_x\, b_y\rangle = -\vec{x}\cdot\vec{y}$, for detection settings $\vec{x}_{0;1} \parallel \vec{y}_{0;1}$, 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 on 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 $p_c(a,b) = (\sum_{m=1}^{N} a_m\ b_m)/N$ 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

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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].

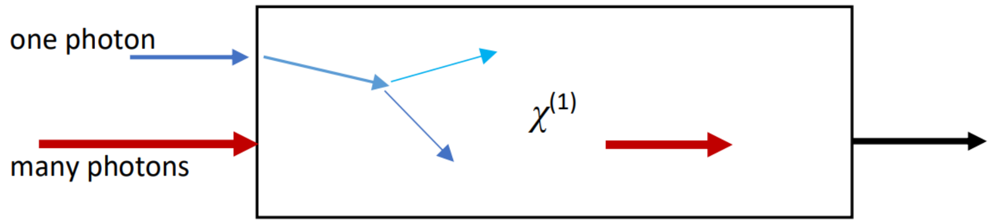

Figure 1. Schematic of one photon being randomly scattered inside a dielectric medium, while a group of identical photons propagates in a straight-line.

Equally, the experimental results of ref. [8] 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 [9] of single photons which will prevent synchronized detections. A physically meaningful explanation was presented in refs. [10,11] 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. [10,11].

Additionally, a sub-section of ref. [2] 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.” [2], (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 “ [2], (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” [2], (p. 466). For a distinction between probability and frequency of occurrence, the reader is directed to ref. [12]

It is claimed that “…quantum correlations cannot be reproduced using no-signaling theories which make more accurate predictions of individual properties compared to quantum theory” [2], (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].

These statements will be disproved in Section 2 by identifying physical probabilities evaluated with independent photons that outperform the quantum correlations based on entangled photons. 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 3 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 4.

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2. Probabilities of independent photons exceeding probabilities 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 allocation 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 $\alpha \; or \; \alpha'$, and $\beta \; or \; \beta'$ leading to the linear combination of probabilities P_{ij} [8], [13]:

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

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, 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., $\alpha \; and \; \alpha'$ as well as $\beta \; and \; \beta'$ 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, [3,4], the inequality is written as:

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

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.

2.2. Linking projective measurements to the theoretical correlation function

Quantum correlations are evaluated as the expectation values of a product of operators [2], [13]. For the projective operators $\hat{\Pi}(\alpha) = |H_\alpha\rangle\langle H_\alpha| \; and \; \hat{\Pi}(\beta) = |H_\beta\rangle\langle H_\beta|$ 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. [2, eq. 13]:

$$p\,(1{,}1;\alpha,\beta) = \left|\left(\langle\psi_{in}|\hat{\Pi}(\alpha)\right)\left(\hat{\Pi}(\beta)\,|\psi_{in}\rangle\right)\right| = \left|\langle\Phi_\alpha|\Phi_\beta\rangle\right| \quad (3)$$

with $|H_\alpha\rangle$ and $|H_\beta\rangle$ identifying the states of the polarization filters, and $\langle\Phi_\alpha| = \langle\psi_{in}|\hat{\Pi}(\alpha)$ 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., $p_c(a,b) = (\sum_{m=1}^{N} a_m \; b_m)/N$, 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.

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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:

$$C(\alpha;\beta) = \langle\Phi_\alpha|\Phi_\beta\rangle = \langle\psi_{in}|H_\alpha\rangle\,\langle H_\alpha|H_\beta\rangle\langle H_\beta|\psi_{in}\rangle \qquad (4a)$$

$$|\psi_{in}\rangle = (\,|H\rangle + |V\rangle\,)/\sqrt{2} \qquad (4b)$$

$$|H_\alpha\rangle = \cos\alpha\,|H\rangle + \sin\alpha\,|V\rangle \quad ; \quad |H_\beta\rangle = \cos\beta\,|H\rangle + \sin\beta\,|V\rangle \qquad (4c)$$

$$C(\alpha;\beta) = 0.5[\cos\alpha + \sin\alpha]\,[\cos(\alpha-\beta)]\,[\cos\beta + \sin\beta] =$$
$$= 0.5\cos(\alpha-\beta)[\cos(\alpha-\beta) + \sin(\alpha+\beta)] \qquad (4d)$$

This correlation of eq. (4d) is composed of three terms. 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 3.

3. 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 $\hat{\Pi}(\beta) = |H_\beta\rangle\,\langle H_\beta|$ acting on the initial state

$$|\psi_{AB}\rangle = (\,|H_A\rangle\,|V_B\rangle - |V_A\rangle\,|H_B\rangle)/\sqrt{2} \qquad (5)$$

and resulting in the probability of detection

$$P_\beta = \langle\psi_{AB}|\hat{I}_A \otimes |H_\beta\rangle\,\langle H_\beta| \otimes \hat{I}_A\,|\,\psi_{AB}\rangle = (\cos^2\beta + \sin^2\beta)/2 = 1/2 \qquad (6)$$

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:

$$|\psi_{B|A}\rangle = |H_\alpha\rangle\,\langle H_\alpha| \otimes \hat{I}_B|\psi_{AB}\rangle = \frac{1}{\sqrt{2}}\,(\cos\alpha\;|V_B\rangle - \sin\alpha\;|H_B\rangle)\,|H_\alpha\rangle \qquad (7)$$

$$|\psi_B\rangle = \frac{|\psi_{B|A}\rangle}{\sqrt{\mathbb{N}}} = \frac{|H_\alpha\rangle\langle H_\alpha| \otimes \hat{I}_B|\,\psi_{AB}\rangle}{\sqrt{\mathbb{N}}} \qquad (8)$$

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. (8) we have:

$$P_\alpha = \langle\psi_{AB}|\hat{I}_B \otimes |H_\alpha\rangle\langle H_\alpha| \otimes \hat{I}_B|\psi_{AB}\rangle = |\langle H_\alpha|\psi_{AB}\rangle|^2 = \mathbb{N}\,\langle\psi_B|\psi_B\rangle = 1/2 \qquad (9)$$

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:

$$P_{\beta|\alpha} = \langle\psi_B|H_\beta\rangle\,\langle H_\beta|\psi_B\rangle = |\cos\alpha\;\sin\beta - \sin\alpha\cos\beta|^2 = \sin^2(\beta-\alpha) \qquad (10)$$

This result which can be found in [13, Sec.19.5] implies that for $\beta - \alpha = \pm\pi/2$, regardless of the values of β or α, the local probability of detection could peak at unity. This theoretical outcome is easily testable experimentally for direct evidence of a quantum nonlocal effect influencing the second

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measurement after the wave function collapse. But this has never been done either because of the quantum Rayleigh scattering [9] of a single-photon and/or the non-existence of such a nonlocal effect. The product of the local probabilities of eqs. (9) and (10) equals the expression of the joint probability $P_{\alpha\beta}$ for simultaneous detections at both locations A and B, that is:

$$P_{\alpha\beta} = \left|\langle H_\beta | \langle H_\alpha | \frac{|\psi_{AB}\rangle}{\sqrt{P_\alpha}}\right|^2 P_\alpha = \left|\langle H_\beta | \psi_B\rangle\right|^2 P_\alpha = P_{\beta|\alpha}\, P_\alpha \qquad (11a)$$

$$P_{\alpha\beta} = \langle \psi_{AB} | H_\alpha\rangle | H_\beta\rangle \otimes \langle H_\beta | \langle H_\alpha | \psi_{AB}\rangle = 0.5\ sin^2(\beta - \alpha) \qquad (11b)$$

$$P_{\alpha\beta} = P_\alpha\, P_{\beta|\alpha} \le P_\alpha\, P_\beta \qquad (11c)$$

after inserting from Eqs. (8) and (10) in the equality (11a). The equality (11b) 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 [13, p.538]. 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 (11a) 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], [13] irrelevant for the derivation of Bell inequalities.

4. The flaws of the quantum nonlocality interpretation of experiments

For the two polarized photons shown in the inset to Figure 1 of [1] "quantum mechanics predicts that the polarization measurements performed at the two distant stations will be strongly correlated." Yet, quantum-strong correlations can also be achieved with independent photons or classical systems [5–7].

Another quotation of interest from [1] 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." 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 [7,9], 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 [7,10,11]; and 3) the experimental evidence of quantum-strong correlations between polarization states or statistical ensembles of multi-photon, independent states [5,6].

The theoretical concept of photonic quantum nonlocality cannot be implemented physically because of the quantum Rayleigh scattering of single photons [9]. Landmark experiments [3,4] 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

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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.

5. Conclusions

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. [14] about the physically meaningful process of Rayleigh scattering of single photons which prevents synchronized detections of the original pair of entangled photons. 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 [14] 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].

Taking into consideration all the flaws and shortcomings of the theoretical claims and experimental outcomes, it is obvious to any impartial physicist that no evidence of a nonlocal quantum effect can be identified. The 2022 Nobel Prize Committee intentionally disregarded the various rebuttals and refutations of the concept of quantum nonlocality in line with the editorial policy of journals such as Physical Review Letters and Physical Review A which knock back without consideration any well-substantiated article outlining the physical reality of Einstein.

For further details see ref. [15].

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