We uncover an apparent instance of classical information transfer via only the Einstein-Podolsky-Rosen channel in a quantum optical protocol between Alice and Bob, involving two-photon maximal path entanglement and based on a recent Innsbruck experiment. The signal is traced to the appearance of coherent reduction due to the onset of spatial degeneracy in the eigenvalue spectrum for Alice’s measurement. We present our result primarily as an issue for experimental testing rather than as a definitive prediction at this stage.

I. INTRODUCTION

Does quantum nonlocality [1], now attested by a vast body of experimental evidence [2–4], consist only in the local inaccessibility of information or, in addition, a nonlocal transfer of information [5]? The answer seems to lie subtly hidden in the quantum formalism. The evidence for spacelike transfer of information remains circumstantial, as in quantum teleportation [6] and remote state preparation [7]—where it can be shown a posteriori that the (in principle, infinite) classical information about a quantum state is nonlocally transferred at the cost of only 2 bits [8]—or controversial, as in the violation of the Bell inequalities [9,3], which tells us that quantum mechanics (QM) cannot be local-realistic. However, it is usually agreed that quantum nonlocality is causal [10]. Here we present a test of the question raised at the beginning.

The article is arranged as follows. The experimental set-up for and the basic idea behind the test are presented in the next section. The main result is derived more rigorously in Section III. This result in physically interpreted in Section IV, where we show that it owes its origin to the onset of eigenvalue spectrum degeneracy in quantum measurement. We then conclude with a final brief section. In view of the absence of a standard method to handle quantum measurement with degenerate outcomes, experimental tests would be valuable in confirming or refuting the effect predicted here to be possible. Further careful scrutiny of the problem is needed also in view of the far-reaching implications of the question considered.

II. EXPERIMENT

The proposed experimental test, based on ideas involved in a recent interesting quantum optical experiment performed by Zeilinger’s group at Innsbruck [11], involves two observers, usually called Alice and Bob, sharing path-entangled biphotons (pairs of entangled photons) from a suitable Einstein-Podolsky-Rosen source at point o. One suggested candidate for the source is a nonlinear crystal (e.g., BBO) with appropriate optical pre-processing, enclosed by the dashed box in Figure 1 which is a ‘folded-out’ schematic of the proposed experiment. The crystal produces polarization-entangled biphotons via spontaneous parametric down-conversion (SPDC) in type II phase matching [12,13], pumped by a suitable laser beam (e.g., Argon laser with λ = 395 nm). A filter restricts outgoing photons to a small bandwidth about the downconverted frequency.

The output from the crystal beyond the dashed box is the maximally entangled state

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|HV\rangle_{AB} - |VH\rangle_{AB}),$$

(1)
where \{|V\rangle, |H\rangle\} represent vertical and horizontal polarization states and subscripts \( A \) and \( B \) represent Alice’s and Bob’s photon. On both sides of the crystal, there is: (1) a polarizing beam-splitter (PBS1 or PBS2) to separate the beams in such a way that eventually the \( H \) beam is parallel to the \( V \) beam; (2) a half-wave-plate (HWP1 or HWP2) in the \( V \) paths to rotate them to \( H \) in order to permit interference (though the labels retain their original polarization values for the sake of uniformity of notation). In this way, maximal polarization entanglement is converted to maximal path entanglement.

Alice is equipped with a lens of focal length \( f \), and a movable detector system that can be positioned at distance \( f \) or \( f - g \) from the lens. Bob is equipped with a Young’s double-slit interferometer, located at distance \( d \) from the plane containing the crystals. By classical optics, parallel rays entering Alice’s lens converge to a single point on the focal plane. Because of path entanglement, a detection by Alice at some point on the focal plane will leave Bob’s photon in a superposition of parallel rays, i.e., a definite ‘momentum state’, but with its point of origin in the source indeterminate, as expected on basis of the Uncertainty principle. This has been confirmed by the interference pattern seen in Bob’s photons detected in coincidence with Alice’s measurement at her focal plane \([11]\). On the other hand, if Alice advances her detector system to a distance closer to the lens, distinguishability is restored and no interference is possible.

In the present protocol, Alice will choose to position her detector at distance \( f \) or \( f - g \) from the lens (Figure 1). Alice’s detector must be wide enough to intercept all \( A \) photons. In practice, one detector element (the scanning tip of a fiber optic element) is sufficient, to be positioned at \( k \), for the focal plane measurement, or at either \( l \) or \( m \), for the off-focal-plane measurement (since a non-detection is also a measurement). Suppose she positions her detector on the plane at distance \( f - g \). She will in effect detect \( A \) at point \( l \) or \( m \). Since her two possible outcomes are distinguishable, and because of entanglement, she correspondingly leaves Bob’s photon in one of the states |\( H \rangle \) or |\( V \rangle \), respectively. Neither detection by her produces an interference in the coincidence counts at Bob’s interferometer because she has acquired path information for Bob’s photon. Therefore, Bob will find no interference pattern on his screen in his single counts.

On the other hand, suppose she positions it at the focus \( k \) of the lens. She will detect a click at point \( k \). Since she cannot distinguish whether her detection was generated by a photon coming through the upper or lower path, by Feynman’s dictum, both paths interfere at \( k \), and, because of path entanglement, correspondingly she is expected to leave Bob’s photon in the superposition state

\[
|M\rangle_B \equiv \frac{1}{\sqrt{2}} (\alpha|H\rangle_B + \beta|V\rangle_B) \quad (|\alpha|^2 + |\beta|^2 = 1),
\]

where \( \alpha \) and \( \beta \) are path dependent phase factors (cf. Section [V]). Therefore, in this case, Bob will find a Young’s double slit pattern in the coincidence counts, produced by the interfering \( H \) and \( V \) rays, rotated by the half-wave-plate HWP2. Further, because the coincidence counts involve only one possible outcome for Alice, he in fact finds the interference pattern in his singles counts.

What evidence do we have that Bob’s photon is indeed projected into the state Eq. (2) by Alice’s focal plane measurement? One way to understand it is to view Alice’s photon \( A \) as a handle on Bob’s photon’s path. Registering \( A \) at \( k \), irreversibly destroys path information about Bob’s photon, so the two \( B \) paths are free to interfere, but otherwise, not. This complementaristic interpretation is well borne out by implementations of the delayed choice experiment [14]. Furthermore, coincidence measurements on two-particle interference experiments [3] clearly show that the point where one of the entangled pair is registered acts like a virtual source for the origin of the modes whose interference determines the probability distribution for the localization of its twin photon. A further corroborations of this reasoning, closer to the experiment at hand, comes from the Innsbruck experiment [11], where it is found that when the signal beam is focussed to a detector using a lens, an interference pattern is detected in the idler coincidence counts, as discussed earlier.

Finally, we want to note that visualizing state |\( M\rangle_B \) as the projection that results from Alice’s measurement is a sort of concession to our quantum mechanical intuition, but is not necessary for the calculation of probabilities in the quantum optical formalism, as shown in the following section. Bob discerns whether Alice measured at the focal plane or not depending on whether or not he finds the tell-tale interference pattern. Clearly, this classical signal can be transmitted arbitrarily fast by increasing \( f \) and/or \( d \) indefinitely. This completes the basic idea of the proposed nonlocal classical signaling test, which will be examined critically in the next two sections.
III. DERIVATION

We now derive quantitatively the result given in the preceding section. The four-mode state vector of the SPDC field incident on Alice’s and Bob’s detectors is given by:

$$|\Psi\rangle = |\text{vac}\rangle + \epsilon(|hv⟩ - |vh⟩)$$

(3)

where $|\text{vac}\rangle$ is the vacuum state, $|h⟩$ and $|v⟩$ are the Fock state modes propagating along the $H$ and $V$ arms of the experiment and $\epsilon(\ll 1)$ depends on the pump field strength and the crystal nonlinearity. The positive frequency part of the electric field at an arbitrary point $z$ on Bob’s screen is:

$$E^+_z = e^{ikr_D} \left( e^{ikr_1} \hat{h} + e^{ikr_2} \hat{v} \right),$$

(4)

where $\hat{h}$ and $\hat{v}$ are the annihilation operators for the $h$ and $v$ modes, respectively. $r_D$ is the distance from the source $o$ via PBS2 to the upper/lower slit on Bob’s double slit diaphragm; $r_1$ ($r_2$) is the distance from the upper (lower) slit to $z$ (Figure 1).

If Alice positions her detector at point $l$ or $m$ on the plane at distance $f - g$ from the lens, the positive frequency part of the electric field at point $l$ or $m$ is

$$E^{(\pm)}_l = e^{ikr_L} \hat{v}, \quad E^{(\pm)}_m = e^{ikr_M} \hat{h},$$

(5)

where $r_L$ ($r_M$) is the distance from $o$ via PBS1 along the upper (lower) path through the lens upto point $l$ ($m$). For simplicity, we set $r_L = r_M$. Now, if Alice positions her detector at the focal plane, the positive frequency part of the electric field at point $k$ is

$$E^{(\pm)}_k = e^{ikr_K} \left( \hat{h} + \hat{v} \right),$$

(6)

where $r_K$ is the distance from $o$ via PBS1 along the upper or lower path through the lens upto point $k$. Again, for simplicity, the distances along the two paths have been taken to be identical.

The coincidence count rate $R$ for simultaneous measurements by Alice and Bob is given by the absolute square of the second order correlation function $\langle \Psi | E^{(+)}_y E^{(+)}_z | \Psi \rangle$. This is proportional to the probability for Alice’s and Bob’s correlated measurements. If Alice positions her detector at point $l$ or $m$ on the plane at distance $f - g$ from the lens, the coincidence rate for detections by Alice and by Bob at $z$ is

$$R_g \propto \langle \langle \Psi | E^{(+)}_y E^{(+)}_z | \Psi \rangle \rangle^2 \propto \epsilon^2,$$

(7)

where $(y = l, m)$ and we have used Eqs. (3), (4) and (6). As the coincidence rates for Alice’s both detections are uniform, Bob finds a uniform intensity pattern on his screen. On the other hand, if she positions her detector at focus $k$, the coincidence rate is given by

$$R_f \propto \langle \langle \Psi | E^{(+)}_k E^{(+)}_z | \Psi \rangle \rangle^2 = \epsilon^2 \{1 + \cos(k \cdot [r_1 - r_2])\},$$

(8)

which is equivalent to a conventional Young’s double slit pattern. Because of the focussing, no other coincidence terms are involved. So the interference pattern Eq. (6) is in fact seen in Bob’s singles counts. In an actual implementation, Eqs. (7) and (8) must be further modified to take into consideration the single slit diffraction pattern and the profile of the down-converted laser beam.

Usually, in biphoton interference experiments, Alice’s photon is not focussed to a single point, but allowed to spread out according to the beam profile or through a single/double slit system. Therefore Bob would see an interference pattern of the type Eq. (6) averaged over various Alice’s detection positions, which smears Bob’s pattern to a uniform distribution that is indistinguishable from that in Eq. (6). In the above experiment, by the focussing of Alice’s beam, this smearing is crucially checked.

Are there some other reasons that come into play that somehow restore the distinguishability between the two paths in Alice’s focal plane measurement? Ultimately, only an experimental test can adjudicate. Suppose Bob’s beam diverges slowly, i.e., $s \theta \ll \lambda$, where $s$, $\theta$ and $\lambda$ are slit-width, divergence angle and wavelength, respectively.
unentangled laser beam satisfying this condition will produce a Young’s double slit pattern. After Alice’s focal plane measurement, Bob’s beam is indeed disentangled into such an unentangled laser beam. Of course, the wavefront of Bob’s disentangled beam will be modified because only annular regions about the lens’s principal axis have the same phase (since they have the same \( R \)). Nevertheless, provided the double slit is positioned symmetrically about the lens’s axis, and Bob’s downconverted (entangled) beam satisfies the usual interference criterion \( s \theta \ll \lambda \), then a possible interesting outcome for the above experiment can be expected.

We note that unlike the case with position-momentum entanglement, a spreading of polarization-entangled light of laser is not required by the Uncertainty principle. Therefore, in principle, polarization-entangled thin pencils satisfying the above slow divergence condition are easier to prepare than position-momentum entangled beams. This is the reason why the present experiment is simpler to implement than that presented in Ref. [15], in which considerable optical preprocessing is needed to bring about a position-momentum entangled equivalent of the above experiment, and which, incidentally, is closer to the Innsbruck experiment [11]. In this regard, we note that that no sudden spreading of \( B \) occurs on account of \( A \)’s localization even if the input is light position-momentum entangled [10].

Two suggestions for the preparation of path-entangled pencils: (1) blocking out photons \( A \) and \( B \) with a shield, except at two small opposing holes, one on each shield, from which fiber optic cables of equal length lead to the respective polarizing beam splitter; (2) selective Bell state measurement using appropriate linear optics on two separable thin laser beams (in this connection, cf. Ref. [17]).

IV. QUANTUM MECHANICAL PICTURE

Although interference experiments rightly belong to the domain of quantum optics (QO), many of them can usually be translated into quantum mechanical language (for example, cf. Ref. [13] as regards the Mach-Zehnder interferometer and Ref. [12] as regards the delayed choice experiment [20,21]). Sometimes the latter version can be easier to physically interpret. Reverting back to the QM notation of Section I we find the reduced density matrix for Bob’s photon if Alice measures in the ‘focal plane’ basis, namely \((\rho_f)_B\), and that if she measures off the focal plane, namely \((\rho_g)_B\), to be

\[
(\rho_f)_B = |M>_B <M|_B = \frac{1}{2}(\alpha|H>_B + \beta|V>_B)(\alpha^*<H|_B + \beta^*<V|_B) \\
(\rho_g)_B = \frac{1}{2}(|H>_B<H|_B + |V>_B<V|_B).
\]

The classicality of the signal is an expression of the fact that \((\rho_f)_B \neq (\rho_g)_B\).

In order to trace the origin of the classical signal, let us interpret the results of the preceding section in the QM Schrödinger picture by inserting the appropriate phase factors. On each path,

\[
|H>_X \rightarrow e^{ik-x_HX}|H>_X; \quad |V>_X \rightarrow e^{ik-x_VX}|V>_X,
\]

where \( x_HX \) (\( x_VX \)) is the distance along the \( H \) (\( V \)) path on beam \( X \) (\( X = A, B \)) from the source at \( a \). Beyond the double slit, \( B \) is transformed into Bob’s screen measurement basis according to:

\[
|H>_B \rightarrow e^{ik-r_1(z)}|z\rangle \quad |V>_B \rightarrow e^{ik-r_2(z)}|z\rangle,
\]

where \( |z\rangle \) is the eigenstate corresponding to \( B \) being found at \( z \), an arbitrary detector element. Bob’s measurement that localizes his particle at \( z \) is given by the usual von Neumann projector, \( \hat{P}_z \equiv |z\rangle\langle z|\).

After inserting the spatial dependences Eqs. (10) and (11) into the biphoton state vector Eq. (8), we have

\[
|\psi\rangle_{AB} \rightarrow \sum_z \left( |H z\rangle_{AB} e^{ik[r_A+r_D+r_2(z)]} - |V z\rangle_{AB} e^{ik[r_A+r_D+r_1(z)]} \right),
\]

with \( r_A \) set to \( r_L = r_M \), for off-focal-plane measurement, or to \( r_K \), for focal plane measurement.

These two measurement planes are equivalent to two different observables. The spectral decomposition for the observable corresponding to measurement on the plane at distance \( f - g \) from the lens can be written as

\[
\hat{O}_g = l|V\rangle_A \langle V|_A + m|H\rangle_A \langle H|_A.
\]
According to the von Neumann projection postulate \[22\], the probability to find \(m\) or \(n\) is given by the expectation value of the corresponding projector

\[
\hat{P}_m \equiv |V\rangle_A \langle V|_A, \quad \hat{P}_m \equiv |H\rangle_A \langle H|_A
\]

in the state \(|\Psi\rangle_{AB}\) in Eq. \[12\] (setting \(r_K\) to \(r_L = r_M\)) \[22\].

The observable corresponding to measurement on the focal plane is seen to be degenerate in space, i.e., both eigenstates \(|H\rangle\) and \(|V\rangle\) have the same position eigenvalue \(k\). Hence, in analogy with Eq. \(13\), we write:

\[
\hat{O}_f = k|V\rangle_A \langle V|_A + k|H\rangle_A \langle H|_A.
\]

(An ‘energetic’ analogy would be switching a magnetic field on or off to render the spin eigenstates of an entangled electron non-degenerate or degenerate in a local energy measurement.) A measurement of position yields the value \(k\), but what is the corresponding projector? Clearly the von Neumann projection postulate cannot handle this case and must somehow be extended. The problem of degenerate measurement was first considered by Lüders \[23\] and has been the subject of recent renewed interest \[24\].

Two related problems here are that of: (a) calculating the probability for obtaining the eigenvalue corresponding to the degenerate subspace and, (b) determining the state in which the system is left if the degenerate eigenvalue is found. The latter problem for QO is necessarily different from that in QM because no particle annihilation figures in QM, unlike in QO. Hence, a QM interpretation is applicable only with respect to the former problem. In Lüders’ formalism for extending the projection postulate, the projector \(\hat{P}_k\) for Alice’s focal plane measurement is given by \(\hat{P}_k = \hat{P}_l + \hat{P}_m\). If valid, this extension would indeed be sufficient to prohibit the classical signaling. However, one can verify that \(\langle \hat{P}_l + \hat{P}_m \rangle \otimes \hat{P}_k\) does not reproduce the interference Eq. \(8\), where \(\langle \cdots \rangle\) represents expectation value with respect to the state Eq. \(12\) setting \(r_A = r_K\). The reason is that it does not permit crosstalk between Bob’s \(H\) and \(V\) modes, needed to explain Bob’s coincident interference pattern in Eq. \(8\), and more generally, the interference seen in coincidence with focal plane detections of \(A\) in the Innsbruck experiment \[11\].

It turns out that the form of the degenerate projector that agrees with Eq. \(8\), and thus rightly represents \(A\)’s electric field in Eq. \(3\), is

\[
\hat{P}_k \equiv \hat{P}_{l+m} = (|H\rangle_A + |V\rangle_A) (|H\rangle_A + |V\rangle_A) \neq \hat{P}_l + \hat{P}_m.
\]

in view of Eq. \(14\). By direct computation, one can verify that \(\langle \hat{P}_{l+m} \otimes \hat{P}_k \rangle\) indeed reproduces the interference Eq. \(8\). This implies that in projecting a state vector to a state corresponding to a degenerate eigenvalue, the amplitudes of the eigenstates in the degenerate subspace superpose. In other words, the probability amplitude that a measurement finds a degenerate eigenvalue is given by the sum of the degenerate amplitudes. The consequences of this for state representation and state vector reduction, both in separable and entangled systems, and experimental tests of whether the validity of such a ‘coherent projection’ and of the associated ‘coherent reduction’ can be extended beyond QO to the case of energy degeneracy in QM proper, are taken up in the future. Coherent reduction brings further richness to the essential quantum phenomenon of superposition. What is encouraging is that quantum optical tests for it are well feasible (in a related vein, cf. Ref. \[25\]).

According to the foregoing analysis, the classical nonlocal signal in the proposed experiment owes its origin to the fact that Alice can choose to make either a von Neumann measurement in the non-degenerate off-focal-plane basis, or a degenerate measurement in the focal plane basis, thereby disentangling Bob’s photon by projecting it completely or coherently. As a result, it requires only the EPR channel and no additional classical communication channel. This is not incompatible with the conclusion of Refs. \[10\], where implicitly only complete von Neumann measurements in a non-degenerate basis are considered.

The new result derived here is in fact implicit in the Innsbruck experiment \[11\], and we would not expect its possible positive outcome if the Innsbruck experiment would not have found interferences in Bob’s coincidence counts for Alice’s focal plane measurement. And yet this latter counterfactual hypothesis would not be possible without the abandonment of the usual quantum optical formalism for calculating interferences at second order. Therefore, the classicality of the signal in a sense lurks in the familiar double slit interference.

V. CONCLUSION

Feynman noted that the central mystery of QM—namely, superposition—is encapsulated by the double-slit interference \[24\]. Coherent reduction, as discussed above, adds a further perspective to this ‘mystery’. Technically speaking,
an (improbable) positive outcome of the experiment is not incompatible with QM itself, since the features of QM that guarantee relativistic causality—namely, linearity\cite{27,28}, unitarity\cite{29}, and the tensor product character of the Hilbert space of composite quantum systems\cite{30}—are essentially non-relativistic. On the other hand, a null result for the proposed experiment, although less obviously explained, would be easier to accept.

\[ \text{References}\]

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FIG. 1. Alice and Bob share a thin pencil of polarization-entangled biphotons in pure state, from an EPR source at o. By means of a pair of polarizing beam splitters (PBS1 and PBS2) and half-wave plates (HWP1 and HWP2), polarization entanglement is converted to path-entanglement. Depending on whether she observes her photon at the focus of her lens, or off the focal plane, she cannot or can obtain path information for Bob’s photon, thereby permitting or prohibiting the latter’s interference. The part of the experiment enclosed in the dashed box prepares the biphoton in used to prepare the biphoton in a path-entangled state.