Can Two-Photon Interference be Considered the Interference of Two Photons?

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We report on a "postponed compensation" experiment in which the observed two-photon entangled state interference cannot be pictured in terms of the overlap of the two individual photon wave packets of a parametric down-conversion pair on a beam splitter. In the sense of a quantum eraser, the distinguishability of the different two-photon Feynman amplitudes leading to a coincidence detection is removed by delaying the compensation until after the output of an unbalanced two-photon interferometer. [S0031-9007(96)01106-4]

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In his famous introduction [1] to the single particle superposition principle, Feynman stated that, "... it has in it the heart of quantum mechanics. In fact, it contains the *only* mystery." Within the context of Young's classic two-slit experiment [2], the role of the observer and the indistinguishability of the "alternative amplitudes" leading to the "final event" have helped exemplify the complementarity inherent in the foundations of quantum mechanics. Yet unlike single particle experiments, the "final events" in two-photon experiments are coincidence measurements, and the notion of these "alternatives" has to be treated with even greater care. For this reason it is important to explicitly demonstrate that two-photon interference cannot simply be pictured as the interference between two single photons.

Consider, for example, the Hong-Ou-Mandel (HOM) two-photon interferometer [3], where the signal and idler photons of a spontaneous parametric down-conversion (SPDC) pair are sent in two beams, a and b, which reflect off mirrors and are then recombined at a beam splitter. When the relative phase delay, δ_{ab}, between these two beams is changed, a destructive two-photon quantum interference effect is seen in the form of a "dip" in the coincidence counting rate when the distances between the crystal and the beam splitter along the two beams are made equal to within the coherence length of the down-converted photons, l_{coh}. Because, loosely speaking, indistinguishability leads to interference, it is quite tempting to rely on a picture which somehow envisions the interference as arising between two individual photons of a given down-conversion pair. For one sees that when the condition for total destructive interference is held, the two optical paths of the interferometer are exactly the same length, and it appears impossible to distinguish which photon caused either single detection event. This concept is further reinforced by the fact that increasing δ_{ab}, which begins to make these path lengths distinguishable, also happens to correspond to a degradation of two-photon interference.

However, the theoretical treatment of HOM [3] and an experiment by Kwiat, Steinberg, and Chiao [4] clearly show that the interference in this type of two-photon experiment is due to the indistinguishability of the various two-photon amplitudes describing the various alternatives leading to a coincidence count. In this type of two-photon picture, there are two such alternatives: the amplitude corresponding to the case in which both photons are reflected by the beam splitter (called r-r) and the amplitude corresponding to the case in which both photons are transmitted by the beam splitter (called t-t). When δ_{ab} is set so that the photons arrive at the beam splitter at the same time these two two-photon amplitudes become completely indistinguishable [5], and two-photon quantum interference is observed. In other words, detectors placed equidistant from the beam splitter fire at exactly the same time, and there is no way, *even in principle*, to determine if it was the r-r or the t-t case which led to the coincidence detection.

Similar effects were observed in the Shih-Alley (SA) type [6] polarization experiments. By inserting a half-wave plate in beam a, the linear polarization ket of the signal photons is rotated from horizontal ($|X\rangle$) to vertical ($|Y\rangle$) so that the t-t and r-r cases, respectively, correspond to the two terms of the Einstein-Podolsky-Rosen (EPR)-Bohm-like state: $|\Psi\rangle \sim (|X\rangle_1|Y\rangle_2 \pm |Y\rangle_1|X\rangle_2)$. Therefore, rotating detector analyzers θ_1 and θ_2 results in the signature $\sin^2(\theta_1 \pm \theta_2)$ coincidence counting rate polarization interference of this entangled state. However, as in the HOM interferometer, the visibility of this polarization interference is reduced as δ_{ab} is increased and the overlap of the photon wave packets at the beam splitter gets smaller and smaller.

Perhaps because these two different pictures appear equally valid in these experiments, the commonly accepted interpretive summary is that in the HOM and SA experiments, interference arises *only* when the photon wave packets overlap at the beam splitter. Although this happens to be true in these particular experiments, it seems that many fall victim to the logical fallacy of extending the results to *all* similar experiments. In fact, it is not uncommon for people to think that in these types of two-photon interference experiments the photons must arrive at the beam splitter at the same time, which seems to imply that some type of classical local interaction was required between two single photons meeting at the beam splitter and "agreeing" which way to go, or how to be polarized.

In this Letter, we hope to dispel this misconception by reporting on a similar type of two-photon experiment in which interference is observed, *even though the photons arrive at the beam splitter at much different times.* In this experiment a picture based on the interference between two individual photons is clearly inapplicable.

The basic ideas of the experiment can be seen in Fig. 1, which is topologically simplified to present the setup in terms of the SA-type polarization version of the balanced HOM interferometer. Here, however, a phase shifter has been placed in the signal beam and set to cause a delay $c\tau_{a_y} \gg l_{\mathrm{coh}}$. Clearly, the photon wave packets *do not* arrive at the beam splitter at the same time: the $|X\rangle$ photon from beam b arrives much before the $|Y\rangle$ photon from beam a. Therefore, just as before, the *welcher weg* information gained, in principle, by the detectors firing at different times renders the two terms of the EPR-Bohm state completely distinguishable, and results in a complete loss of interference.

But what if we could somehow compensate for this delay *after* the interferometer in such a way that the detector firing times do not provide any information concerning which of the two-photon alternative amplitudes led to the coincidence detection? Could we then restore the quantum coherence and revive the interference? The answer is "yes."

One way we can perform this type of "postponed compensation" is to simply place a "compensator" in one of the output ports of the beam splitter [7]. As shown in Fig. 1, the compensator requires the $|X\rangle$ polarized idler photons to take a long path of relative delay τ_{1_x} compared to the $|Y\rangle$ polarized signal photons.

With the analyzers at 45°, we now set the delay of the compensator *twice* as large as the pre-beam-splitter delay ($\tau_{1_x} = 2\tau_{a_y}$) and consider the two possible amplitudes leading to a coincidence detection, which are shown through the Feynman-like diagrams of Fig. 2. In the r-r case we see that the detectors do not fire at the same time because D_1 is triggered after the relative delay τ_{a_y}. However, in the t-t case, it is D_2 which is triggered after delay τ_{a_y}, but D_1 fires even later, corresponding to the relative delay τ_{1_x}. The end result is that in each case D_2 fires before D_1 by the same amount of time [8]. Therefore, even though the different optical paths leading to each individual detector are completely distinguishable, it is important to note that the two two-photon amplitudes are completely indistinguishable by the coincidence measurement, and we can therefore see quantum interference between them.

So with $\theta_1 = \theta_2 = \pm 45°$ [9], scanning τ_{1_x} past the value $2\tau_{a_y}$ results in a HOM dip (or peak) in the coincidence counting rate. Here, however, there is an overall phase difference between the two indistinguishable two-photon amplitudes, and so we can expect this peak-dip "envelope" to be filled with standard idler frequency oscillations [10],

$$R_c(\tau_{1_x}) = 1 - \cos(\omega_x \tau_{1_x}) e^{(-\sigma^2/2)(2\tau_{a_y} - \tau_{1_x})^2}, \quad (1)$$

where ω_x is the idler frequency, and σ is inversely proportional to l_{coh}.

Near the bottom (or top) of this envelope the two terms of the EPR-Bohm state are completely indistinguishable, and we should be able to rotate the analyzers and see

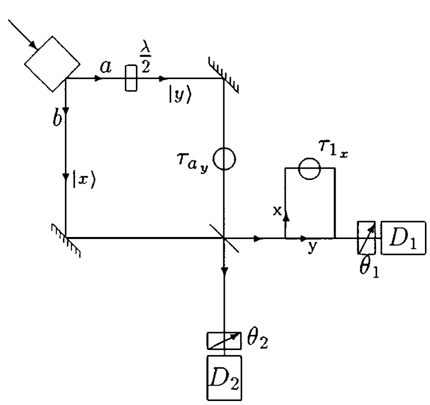

FIG. 1. Schematic representation in terms of the HOM interferometer. Although the photons do not arrive at the beam splitter at the same time, indistinguishability may be preserved by compensating *after* the interferometer.

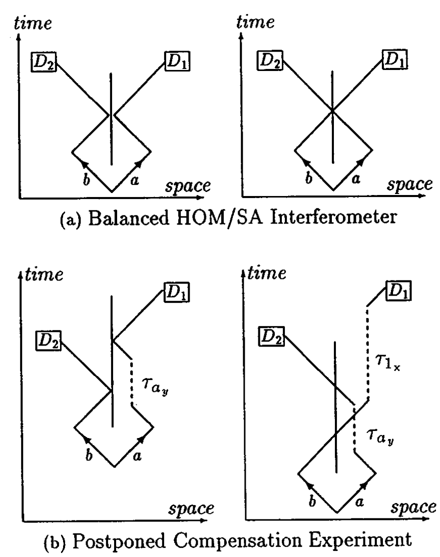

FIG. 2. Conceptual Feynman-like diagrams of the r-r case (left sides) and t-t case (right sides), with the familiar HOM and SA example shown for reference. The beam splitter is represented by the thin vertical lines. In the postponed compensation experiment, the relative delays are indicated by vertical dashed lines, and it is clear that in each case the photons do not arrive at the beam splitter at the same time. Note that the misconception of single photon paths being equated with the two-photon "alternatives," which happens to work in the HOM and SA example, clearly falls apart in the postponed compensation experiment.

the polarization interference. As shown below, these expected standard two-photon interference patterns were exactly what was observed in our experimental realization of postponed compensation.

Rather than using type-I SPDC and a half-wave plate in the signal beam, the actual experimental setup took advantage of type-II SPDC [11], in which the photons of a given down-conversion pair naturally emerge from the crystal with orthogonal polarizations. Furthermore, the noncollinear geometry shown in Fig. 1 was replaced by a collinear one in which the degenerate wavelength signal and idler photons exit the crystal in the same direction as the pump and their optical paths leading to the single input port of the beam splitter are equivalent to beams a and b in Fig. 1.

Shown schematically in Fig. 3, this type-II SPDC was achieved by sending roughly 300 mW of the 351.1 nm line of an argon-ion laser into a 0.5 mm thick β-BaB_2O_4 (BBO) crystal whose optic axis was cut at 49.2° with respect to the pumping beam direction.

The pump beam was then separated from the 702.2 nm degenerate wavelength down-conversion beam by means of a UV grade fused silica dispersion prism, and sent to a beam dump. Detector packages, which consisted of a rotatable Glan-Thomson polarizing prism (analyzer) followed by a 10 nm bandwidth spectral filter and a strong collection lens which focused all of the incoming light onto a single photon counting avalanche photodiode, were placed roughly 1 m away in each of the output ports. The output pulses of the detectors were sent to a coincidence circuit with a 2.3 ns acceptance window, thereby ensuring spacelike separated detection events.

In this collinear configuration the pre-beam-splitter delay τ_{a_y} was realized by inserting a 20 mm quartz rod with its fast axis aligned parallel to the $|X\rangle$ direction and its slow axis parallel to the $|Y\rangle$ direction. At wavelengths around 702.2 nm this birefringent rod delayed the $|Y\rangle$ signal photons relative to the $|X\rangle$ idler photons by imposing an optical path length difference of roughly 180 μm. Since l_{coh}, which is primarily determined by the 10 nm spectral width filters, is only about 50 μm (in fact, the "natural" coherence length defined by this crystal is even smaller—roughly 20 μm [11]), the wave packets are separated by more than 3 times their coherence length, and it is safe to say that they do not arrive at the beam splitter at the same time.

To implement the compensator shown in Fig. 1, two more identical 20 mm quartz rods were placed in the output port of the beam splitter leading to D_1. These rods, however, were rotated by 90°, thereby forcing the $|X\rangle$ photons to take the relative "long path," and the compensation condition $\tau_{1_x} = 2\tau_{a_y}$ was held. In order to "scan" τ_{1_x} around this condition and observe the envelope interference pattern, we placed eight 1 mm thick quartz plates after these two rods. The relative optical delay caused by each plate was roughly 9 μm. Unlike the rods, however, these quartz plates were *not* rotated by 90°, essentially "shortening" the long path of the compensator so that $\tau_{1_x} < 2\tau_{a_y}$. By removing these plates one by one, the effective "length" of the long path was increased until $\tau_{1_x} = 2\tau_{a_y}$.

We then rotated these same plates by 90° and *reinserted* them one by one, thereby increasing the long path of the compensator so that $\tau_{1_x} > 2\tau_{a_y}$. Slightly tilting one of the quartz rods upon removal or insertion of the plates allowed us to adjust the overall phase delay on the order of the much smaller scale idler frequency oscillations. In this way each of the data points was taken resting along the edge of the dip-peak envelope, allowing the interference effect to be clearly seen (see Fig. 4).

At the bottom of the dip (e.g., $\tau_{1_x} = 2\tau_{a_y}$), we rotated the analyzers to see the $\sin^2(\theta_1 - \theta_2)$ polarization interference [12] shown in Fig. 5.

In addition to simply demonstrating this new effect, the high visibility of the polarization interference fringes could even be used to test Bell's inequality [13]. Furthermore, this type of postponed compensation offers yet

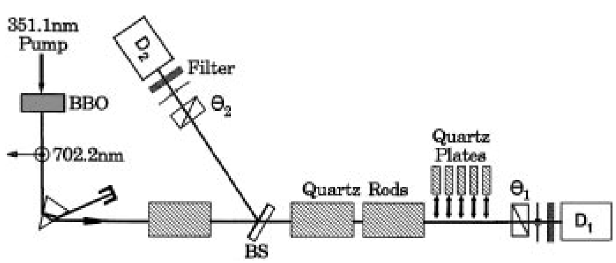

FIG. 3. A schematic of the actual experimental setup. Collinear type-II phase matched SPDC provides pairs of orthogonally polarized photons which enter a single input port of a beam splitter. Birefringent quartz rods and plates are used to implement the delays τ_{a_y} and τ_{1_x}.

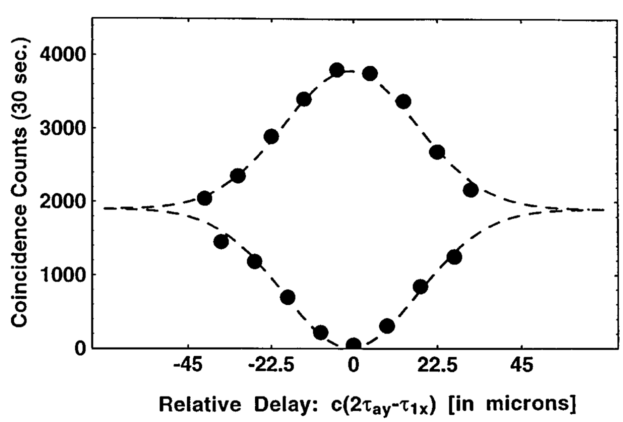

FIG. 4. Experimental data demonstrating the expected peak-dip "envelope" interference pattern. As explained in the text, each point corresponds to a 1 mm quartz plate being inserted or removed from the system, and the width is seen to correspond to l_{coh} [3]. The dashed line is a Gaussian fitting.

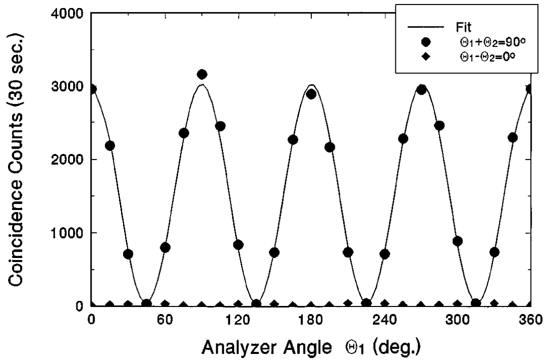

FIG. 5. Polarization interference at the bottom of the peak-dip envelope. The solid line is a $\sin^2(\theta_1 - \theta_2)$ fitting, with $(97.3 \pm 1.9)\%$ visibility.

another experimental realization of the "quantum eraser" phenomenon [4,14] in the following sense: Without the compensator in place, the detector firing times offer, in principle, complete *welcher weg* information about which amplitude led to the coincidence detection.

By inserting the compensator, we erase this information and restore the interference pattern. Finally, we note that the idea of replacing the input to the compensator in the schematic of Fig. 1 with a suitable fast optical switch could allow for a practical demonstration of the "delayed choice" concept [15].

In conclusion, the results of this experiment clearly demonstrate that two-photon interference effects can be observed even when the optical paths in the interferometer have very different lengths, and the photons do not arrive at the beam splitter at the same time. In several earlier polarization experiments [6] the intuitively comforting notion of the photons overlapping at the beam splitter is not at the heart of the interference, but a mere artifact of the particular geometry of the setups. What is important is the indistinguishability of the two-photon amplitudes, which may be maintained or destroyed *after* the output of the interferometer. This type of postponed compensation highlights the nonclassical nature of the two-photon state produced in SPDC, which cannot simply be thought of as two single photons.

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[7] A simpler, but less interesting, way to achieve this postponed compensation is to put a compensator in *each* of the output ports, with delays $\tau_{1_x} = \tau_{2_x} = \tau_{a_y}$.
[8] The idea of registering a "coincidence count" with different detector firing times is not troubling. Note that since D_2 always fires before D_1, we could simply move D_2 farther away from the beam splitter (see Ref. [5]).
[9] As demonstrated in [4], by setting the analyzers orthogonal to each other $(\theta_1 = -\theta_2 = 45°)$ the destructive interference which gave the dip can be made constructive, resulting in a "peak."
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