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Two-photon interference without bunching two photons

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Abstract

We report an experiment which conclusively demonstrates that the two-photon entangled state interference cannot be pictured as the overlap and 'bunching' of two individual photons on a beamsplitter. We also demonstrate that photon 'bunching' does not occur if the two-photon Feynman amplitudes are distinguishable, even though individual photons do overlap on a beamsplitter.

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Two-photon quantum interference effects in spontaneous parametric down-conversion (SPDC) [1] fields have been playing an important role from the study of fundamental problems of quantum physics [2,3] to recent advances in quantum cryptography [4] due to the entanglement between the two down-converted photons.

Among many different quantum interference effects in SPDC, the observation of null (experimentally, close to zero) coincidence counts between the detectors placed at the two output ports of a beamsplitter, when two SPDC pair photons are brought back together on the beamsplitter from the different input ports at the same time, has attracted a lot of attention over the years. It was first observed by Shih and Alley [5,6] and later by Hong, Ou, and Mandel [7, 8]. This effect, which we refer to as SA/HOM effect, has the following formal interpretation: because the two two-photon (or biphoton) amplitudes leading to a coincidence count (both photons are reflected at the beamsplitter, r–r, or both photons are transmitted at the beamsplitter, t–t) become indistinguishable, *even in principle*, when the photons arrive at the beamsplitter simultaneously from the different input ports, fourth-order two-photon quantum interference occurs. Due to the destructive nature of the interference (each photon accumulates i phase shift upon reflection at the beamsplitter) between r–r and t–t amplitudes, zero coincidence counts are expected [7–9].

This formal interpretation is, however, always accompanied by a physical picture that two individual photons somehow become bunched together at the beamsplitter when they arrive at the same time. Since now bunched two photons leave the beamsplitter from the same output port, null coincidence is expected. Due to this picture, it is indeed quite common for researchers to think that two photons must overlap at the beamsplitter for these types of two-photon interference effects to occur [10]. Such a picture, however,

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gives too much credit for the SA/HOM effect to a simple linear optical beamsplitter since it implies some types of local nonlinear interactions between photons.

Is the overlap of the two down-converted SPDC photons at a beamsplitter indeed necessary for the SA/HOM effect? Pittman et al. first reported an experiment which dealt with this question [11]. In their experiment, a delay, which is bigger than the individual photons' coherence times, introduced to one photon before the beamsplitter is compensated by twice the delay introduced to its twin photon after the beamsplitter (postponed compensation). They were then able to observe the SA/HOM effect even though the two photons did not actually overlap at the beamsplitter. However, the laser which pumps the SPDC process must have the coherence time much bigger than the delay introduced between the photon pairs for Pittman et al.'s scheme to work. In fact, a cw Argon ion laser, which had several orders of magnitude bigger coherence time than the delay time, was used in their experiment. In other words, the individual SPDC photons should arrive (or 'overlap') at the beamsplitter within the coherence time of the pump photon in order for Pittman et al.'s scheme to demonstrate the SA/HOM interference. Thus, the result of Pittman et al.'s experiment does not provide us with a complete answer to the question.

In this Letter, we wish to report an experiment which conclusively demonstrates that the 'photons overlapping and bunching at the beamsplitter' picture is not a valid explanation of the general SA/HOM effect (whether 'photons' refer to the pump photons or the SPDC photons). In this experiment, the two photon-wavepackets not only never overlap at the beamsplitter but also the arrival time difference between the photon pair at the beamsplitter is much bigger than the coherence time of the pump photon. Therefore the 'photon bunching' picture is simply not applicable to this scheme. We also present an experiment in which the SPDC photons do overlap at the beamsplitter, but the SA/HOM interference does not (and cannot) occur. The quantum mechanical picture based on in(distinguishability) of 'two-photon amplitudes', however, correctly predicts the presence (absence) of the interference.

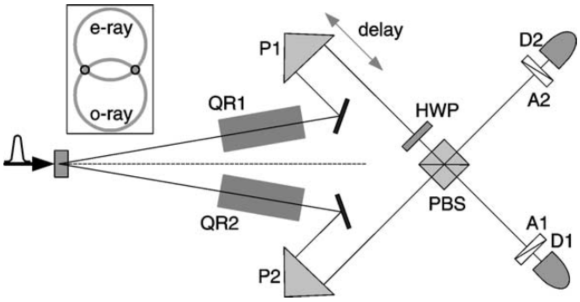


Fig. 1. Schematic of the experiment. QR1 and QR2 are 20 mm long quartz rods, HWP is a $\lambda/2$ plate oriented at 45°.

The basic idea of the experiment can be seen in Fig. 1. The photon pair is generated from a 3 mm thick type-II BBO crystal, with its optic axis oriented vertically, pumped by an ultrafast laser pulse with coherence time of approximately 120 fs. The pump pulse, vertically polarized, has the central wavelength of 390 nm and the wavelengths of the SPDC photons are centered at 780 nm. As in Ref. [12], we consider the intersections of the cones made by the *e*- and *o*-rays exiting the BBO crystal. In each of these two directions, a photon of either polarization (horizontal or vertical) may be found, with the orthogonal polarization found in the conjugate photon (i.e., individual photons are unpolarized). Note that, unlike common misconception, the photon pairs found in these two directions are not polarization entangled. In fact, the polarization state of the photon pair is in a mixed state. For a cw pumped type-II SPDC, polarization entanglement can be obtained by local operations [13]. For a femtosecond pulse pumped type-II SPDC, it is in general not possible to achieve polarization entanglement [14–16].

Each photon then passes through a 20 mm long quartz rod (QR1 and QR2), which generates a relative group delay between the two photons, depending on the polarization of the photon and the orientation of the optic axis of the quartz rod. The polarization of one of the photons is then flipped by a 45° oriented half-wave plate (HWP). The interferometer is completed by a polarizing beamsplitter (PBS) and the delay between the two arms is introduced by moving one of the two trombone prisms (P1 and P2). Photon pairs are then detected by two single-photon counting modules (D1 and D2) after passing through polarizers (A1 and A2). In front of each detectors, a 20 nm FWHM interference filter is introduced to reduce background noise. The outputs from the two detectors were fed to a time-to-amplitude converter (TAC) and the TAC output was analyzed by a multi-channel analyzer with a coincidence window set to 3 ns.

Let us first consider the case in which the SA/HOM effect is observed even though the photons never overlap at the beamsplitter (the arrival time difference between the photons at the beamsplitter is much greater than the coherence times of the pump photon and the SPDC photons). This case can be realized by setting the optic axes of both QR1 and QR2 vertically. As explained before, there are two possibilities for the polarization state photon pair; $|H_o\rangle|V_e\rangle$ or $|V_e\rangle|H_o\rangle$. $|H\rangle$ and $|V\rangle$ refer to the orientation of the polarization of the photon, horizontal and vertical, respectively and the subscripts e and o refer to whether the photon belongs to the e-ray or o-ray of the crystal, initially. For example, $|H_o\rangle$ refers to the photon polarized horizontally and belongs to the o-ray of the crystal. Note, however, that $|H_e\rangle$ can never occur due to the orientation of the BBO crystal.

Since the optic axes of both quartz rods are oriented vertically (i.e., fast axis oriented horizontally), a horizontally polarized photon experiences relatively less group delay with respect to its vertically polarized twin. This relative delay is calculated to be approximately $T \approx 630$ fs for 20 mm long quartz rods used in this experiments. This delay T is much bigger than 120 fs pump pulse coherence time and the coherence times of the SPDC photons which are defined by the bandwidth of the interference filters: $\tau \sim \lambda^2/(c \cdot \Delta\lambda) \approx 100$ fs. Note that the delay T is different from the relative delay between the two arms of the interferometer which is introduced by moving P1.

This situation is well represented in the Feynman-like spacetime diagram shown in Fig. 2(a). Since the HWP transforms the polarization state $|H\rangle \leftrightarrow |V\rangle$, there are only two possible two-photon amplitudes: both photons reflected (r–r) or both photons transmitted (t–t). It is not hard to see that the arrival time difference between the photon pair at the beamsplitter, T, is much bigger than both the coherence times of the photons themselves, τ, and the pump pulse. However, if the both arms of the interferometer have the same length (P1 delay $= 0$ fs), the amplitudes r–r and t–t cannot be distinguished by the arrival times of the photons (even with infinitely fast photodetectors). The only distinguishing information for the two amplitudes is in their polarization and it can be erased by setting the polarization analyzers either at A1/A2 = 45°/45° or at 45°/(−45°). (For more information on quantum eraser, see Refs. [9,11,17,18].) Therefore, even though the two photons never overlap at the beamsplitter and the arrival time difference is much bigger than the pump coherence time, the SA/HOM effect may still occur. This is because the SA/HOM effect, in general, is the result of indistinguishability between two two-photon amplitudes but not due to 'photon bunching at beamsplitter' effect.

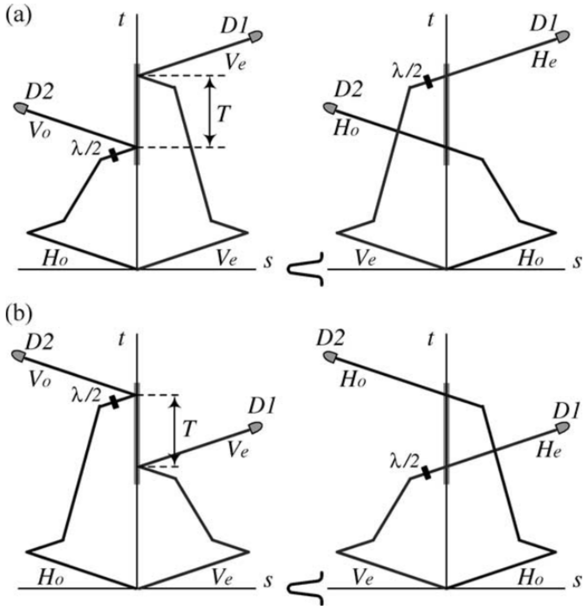


Fig. 2. Possible quantum mechanical amplitudes (r–r and t–t) for a photon pair can take when the optic axes of (a) both QR1 and QR2 are oriented vertically, (b) both QR1 and QR2 are oriented horizontally. Vertical (horizontal) axis represents time (space). Thick gray line at the center represents the polarizing beamsplitter (PBS). It is important to remember that although the photon-pair detection amplitudes can be represented in this way, individual photons are completely unpolarized in this experiment.

We can also consider when both QR1 and QR2 are horizontally oriented. In this case, nothing is changed except that the delays experienced by each photons are reversed. The two-photon amplitudes for this case can be seen in Fig. 2(b). It is clear that the two-photon amplitudes remain indistinguishable however the order in which the detectors fire has been reversed. In Fig. 2(a), D2 always fires before D1 by time T. In Fig. 2(b), D1 always fires before D2 by the same amount of time.

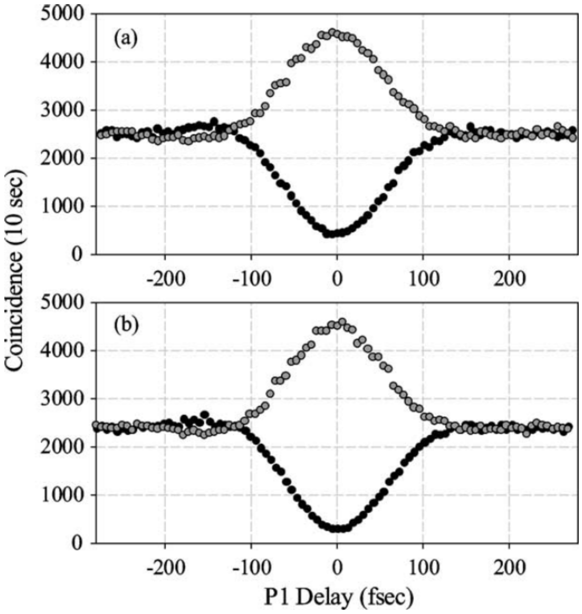
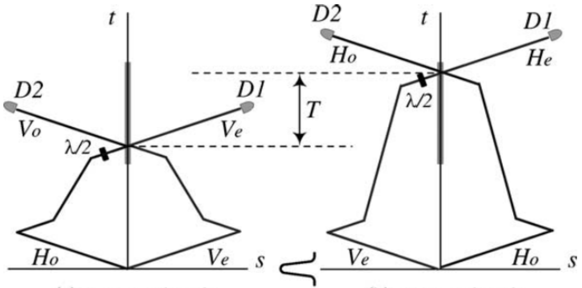


Fig. 3. High visibility quantum interference is observed (a) when both QR1 and QR2 are oriented vertically ($V \sim 83\%$), see Fig. 2(a); (b) when both QR1 and QR2 are oriented horizontally ($V \sim 87\%$), see Fig. 2(b). ‘Dip’ (dark circle) is observed for 45°/45° and ‘peak’ (gray circle) is observed for 45°/(−45°) analyzer angles (A1/A2).



(a) *r-r amplitude* (b) *t-t amplitude*

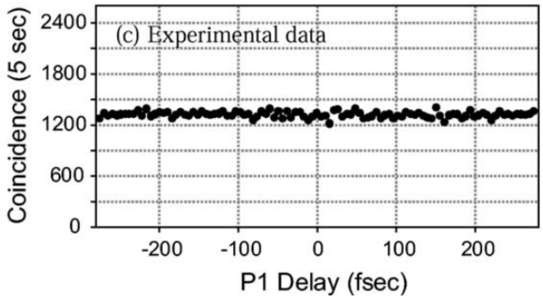


Fig. 4. Possible quantum mechanical amplitudes when the optic axis for QR1 (QR2) is set at vertical (horizontal). In this case, individual photons do overlap at the beamsplitter in both amplitudes. However, due to the intrinsic distinguishability between the two amplitudes, quantum interference (SA/HOM effect) cannot occur. (c) Experimental data showing no interference. Analyzer angles are 45°/45°.

The experimental data for these two cases are shown in Fig. 3. When taking the data, we fixed the orientations of the quartz rods and scanned the interferometer arm delay by moving the trombone prism P1. This procedure was repeated for different orientations of quartz rods for two different analyzer settings: A1/A2 = 45°/45° and 45°/(−45°). The observed visibilities are higher than the classical limit (50%) as well as the limit for the Bell-inequality violation (71%) which clearly establishes that the observed interference is of quantum origin.

Let us now consider the case in which two down-converted SPDC photons do overlap at the beamsplitter, yet no quantum interference (SA/HOM effect) can occur. To consider this case, we need to choose orientations of the quartz rods other than both vertical and horizontal. Here we consider $\mathrm{QR1} = V$ and $\mathrm{QR2} = H$. In this case, the photon pair experiences the same group delay in both arms of the interferometer because the photon pair has the polarization state $|H\rangle|V\rangle$ or $|V\rangle|H\rangle$. The Feynman diagram for this case can be seen in Fig. 4(a) and (b). It is clear that the individual photons do overlap at the beamsplitter for both r–r and t–t amplitudes. However, the two amplitudes are intrinsically distinguishable because if we had infinitely fast detectors, the pump pulse would act as a clock and we would then be able to distinguish the two amplitudes. However, should the SA/HOM effect be a result of ‘photon bunching’, a dip or peak in coincidence counts should occur. We have done this experiment and observed no interference for any polarizer settings, see Fig. 4(c). This clearly shows that the photon bunching picture often used in literature is indeed incorrect in general and should not be used whenever possible.

Note that the experiment discussed in Fig. 4 can be seen as a generalized experimental demonstration of the clock effect of the pump pulse first studied theoretically in Ref. [14]. Although the clock effect discussed in Ref. [14] comes from rather subtle differences in the group velocities between the pump pulse and the SPDC photons in the nonlinear crystal itself, it can be easily generalized to any situations in which two quantum amplitudes carry time tags: unless the time tags are completely erased, interference does not occur. The experiment discussed in Fig. 4 is the first experimental demonstration of such a generalized clock effect. Here, the time differences between the pumping pulse and the detector firing times can, *in principle*, be used to distinguish between the two amplitudes shown in Fig. 4(a) and (b). Although such distinguishing time information is less than 700 fs which is practically not possible to measure with current single-photon detectors, the fact that they are distinguishable in principle is enough to destroy the quantum interference completely, see Fig. 4(c). To erase the time tags associated with each amplitudes, one simply needs to change the coherence time of the pump pulse so that it is much bigger than the delay time T. The uncertainty provided by a long coherence time of the pump pulse would then make the two amplitudes indistinguishable in time, thus reviving the interference. We are then back to the situation where the photon bunching picture and the quantum amplitude picture both are valid and this situation is similar to Pittman et. al.'s scheme. It is therefore necessary that, to be able to make a clear distinction between the two pictures, all relevant coherence times should be much smaller than the photon arrival time difference at the beamsplitter.

To summarize, we reported a quantum interference experiment in which two-photon quantum interference was observed even though the photon pair arrival time difference at the beamsplitter was much greater than the coherence times of the individual photons as well as the pump pulse. We have also discussed the case in which photons did overlap at the beamsplitter but no quantum interference could be observed. This experiment clearly demonstrates that the SA/HOM effect is indeed due to indistinguishability of two-photon amplitudes but not due to the 'photon bunching' effect of individual photon wavepackets. It also demonstrates that genuine higher-order interference effects should not and cannot be explained by using lower-order interference picture. Dirac, in his famous textbook, stated "Each photon then interferes only with itself [19]". In two-photon interference experiments, we may then say "Two-photon or biphoton interferes only with itself". The entangled two-photon (or any two or more particles in an entangled state), therefore, should be viewed as a single nonlocal physical object [20–22].

Finally, we note that this work may be of some use in quantum cryptography and in studying decoherence management in entangled two-qubit systems as we observe near complete restoration of quantum interference (without any post-selection in principle) after the qubit pairs (which are in mixed states), generated by a femtosecond laser pulse, went through certain birefringent elements [23,24].

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