Two-Photon Interference without Bunching Two Photons

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We report a novel interference experiment in which the two-photon entangled state interference cannot be pictured in terms of the overlap and bunching of two individual down-converted photons on a beamsplitter. Experimentally, this is accomplished by choosing the arrival time difference between the two photons at the beamsplitter much bigger than the coherence time of the pump pulse as well as the coherence times of the individual photons. We also experimentally demonstrate that two-photon interference, or photon bunching effect on a beamsplitter, does not occur if the two-photon Feynman amplitudes are distinguishable, even though individual photons do overlap on a beamsplitter. Therefore, two-photon interference cannot be viewed as interference of two individual photons, rather it should be viewed as two-photon or biphoton interfering with itself. The results may also be useful for studying decoherence management in entangled two-qubit systems as we observe near complete restoration of quantum interference after the qubit pairs, generated by a femtosecond laser pulse, went through certain birefringent elements.

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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] to recent demonstrations of quantum cryptography [3] due to the entanglement between the two down-converted photons.

Among many different quantum interference effects in SPDC, the observation of null (or close to zero) coincidence counts between the detectors placed at the two output ports of a beamsplitter, when two photons of SPDC 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 [4] and later by Hong, Ou, and Mandel [5]. This effect, which we refer to as SA/HOM effect, has the following formal interpretation: The two-photon interference occurs because the two two-photon 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*, and cancel each out when the photons arrive the beamsplitter simultaneously. Due to the destructive interference (because each photon accumulates i phase shift upon reflection at the beamsplitter) between r-r and t-t amplitudes, null coincidence counts are expected [5, 6].

This formal interpretation is, however, always accompanied by a physical picture that two individual photons somehow become bunched together at the beamsplitter when arrived 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 people to think that two photons must overlap in time at the beamsplitter for these types of two-photon interference effects to occur [7]. Such a picture, however, gives too much credit for SA/HOM effect to a simple linear optical beamsplitter since it implies some types of local nonlinear interactions.

We now ask: Is the overlap of the two down-converted SPDC photons indeed necessary for SA/HOM effect. Pittman *et al.* first reported an experiment which dealt with this question [8]. 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 SA/HOM effect even though the two photons did not overlap at the beamsplitter. However, the laser which pumps the SPDC process must have 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. Since it is known that the entangled photon pair of SPDC collectively has the properties of the pump photon, it may be said that the SPDC photons do overlap at the beamsplitter within the coherence time of the pump photon in Pittman *et al.*'s scheme. Thus, Pittman *et al.*'s experiment does not provide us with a clear answer to the question.

In this paper, we wish to report an experiment which conclusively demonstrates that the 'photons overlapping and bunching at the beamsplitter' picture is not a valid

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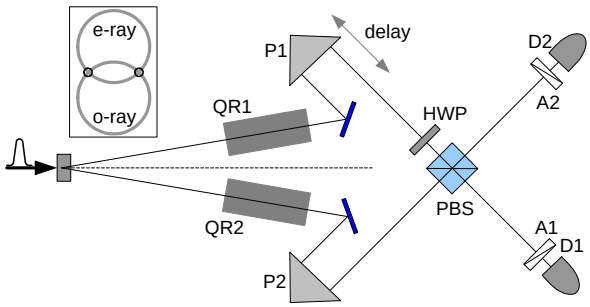

FIG. 1: Schematic of the experiment. QR1 and QR2 are 20 mm long quartz rods, HWP is a $\lambda/2$ plate oriented at 45°.

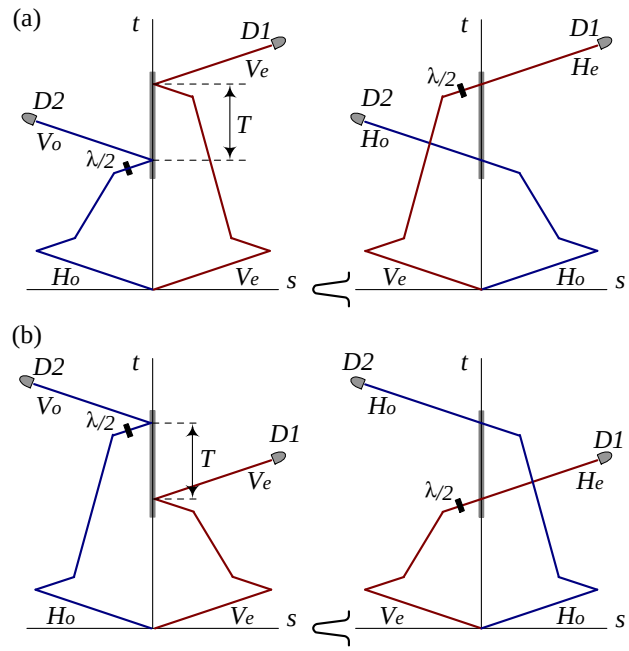

FIG. 2: Possible quantum mechanical amplitudes for a photon pair can take when the optic axes of (a) both QR1 and QR2 are oriented vertically, (b) both QR1 and QR2 are oriented horizontally. Vertical (horizontal) axis represents time (space). Thick gray line represents the polarizing beamsplitter (PBS).

explanation of 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 (pulse). 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 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.

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 130 fsec. 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. [9], 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 [10]. Each photon then pass through a 20 mm long quartz rod (QR1 and QR2). Depending on the polarization of the photon and the orientation of the optic axis of the quartz rod, the photon acquires a relative group delay with respect to its twin photon, which also gets delayed accordingly. The polarization of the one of the photon 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 are 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 nsec.

Let us first consider the case in which 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 the vertically polarized its twin. This relative delay is calculated to be approximately $T \approx 630$ fsec for 20 mm long quartz rods used in this experiments. This delay T is much bigger than 130 fsec

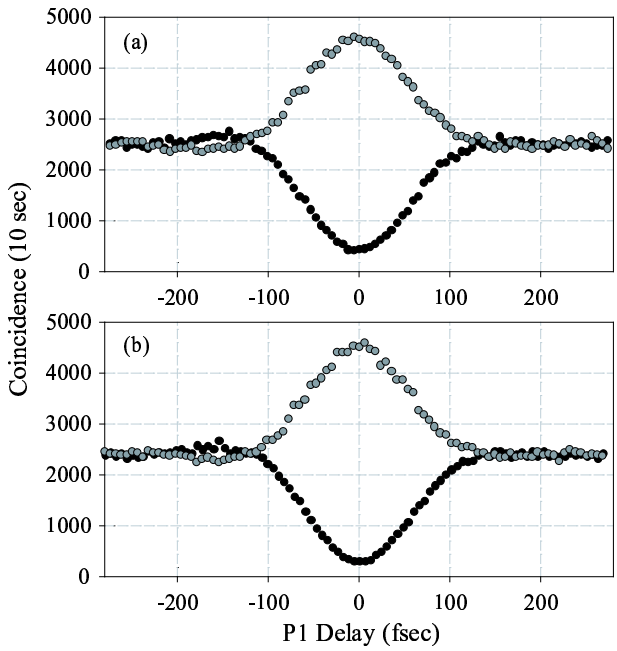

FIG. 3: High visibility quantum interference is observed (a) when both QR1 and QR2 are oriented vertically ($V \sim 83\%$), see Fig. 2(a) and (b) when both QR1 and QR2 are oriented horizontally ($V \sim 87\%$), see Fig. 2(b). 'Dip' is observed for $45°/45°$ and 'peak' is observed for $45°/-45°$ analyzer angles (A1/A2).

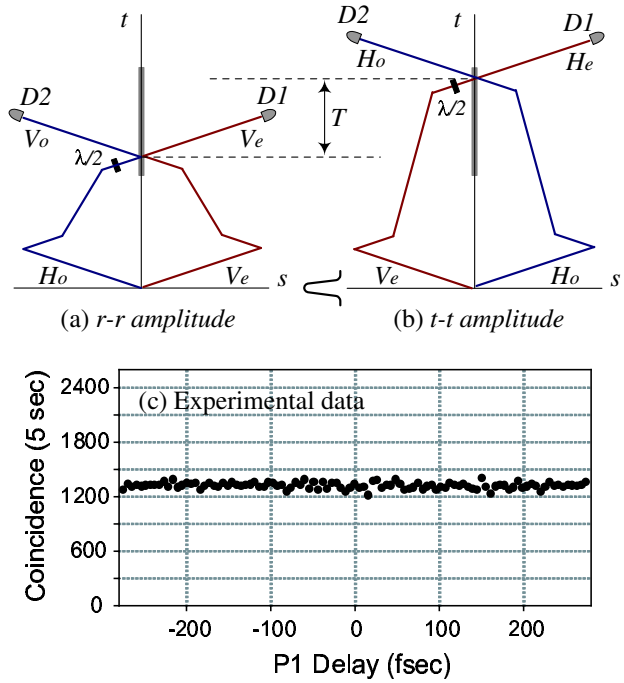

FIG. 4: Possible quantum mechanical amplitudes when the optic axis for QR1 (QR2) is set at vertical (horizontal). Individual photons do overlap at the beamsplitter in both amplitudes. However, due to the intrinsic distinguishability between the two amplitudes, quantum interference (SA/HOM effect) cannot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

pump pulse coherence time and the coherence times of the SPDC photons which are defined by the bandwidth of the interference filters: $\tau \sim \lambda^2/(c \cdot \Delta\lambda) \approx 100$ fsec. 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 space-time 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 fsec), 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 $45°/-45°$ [12]. Therefore, even though the two photons never overlap at the beamsplitter and the arrival time difference is much bigger than the pump coherence time, SA/HOM effect may still occur. It is because SA/HOM effect, in general, is the result of indistinguishability between two two-photon amplitudes but not due to 'photon bunching at beamsplitter' effect.

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 reversed. In Fig. 2(a), D2 always fires before D1 by time T. In Fig. 2(b), D1 always fires before D1 by the same amount of time.

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 procedures were 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 roads other than both vertical and horizon-

tal. Here we consider QR1 = V and 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 Fig. 4(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 SA/HOM effect a result of 'photon bunching', a dip or peak in coincidence counts should occur. We have done this experiment and observed no interference in any polarizer settings, see Fig. 4(c). This clearly shows that the photon bunching picture often used in literature is indeed incorrect and should not be used whenever possible.

Note that it is, however, possible to observe interference if the pump pulse coherence time is bigger than T in Fig. 4. The uncertainty provided by a long coherence time of the pump pulse would then make the two amplitudes indistinguishable, thus leading to interference. We are then back to the situation where the photon bunching picture and the quantum amplitude picture are both valid. This situation is then similar to Pittman et al's scheme. It is therefore necessary that all relevant coherence times should be much smaller than the photon arrival time difference at the beamsplitter to be able to make a clear distinction between the two pictures.

To summarize, we reported a novel quantum interference experiment in which two-photon quantum interference was observed even though the photon pair arrival time difference at the beamsplitter was much bigger 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 (had been) observed. This experiment clearly demonstrates that 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 [13]." In two-photon interference experiments, we may then say "Two-photon or biphoton interferes only with itself [14]."

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 [15].

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