Two-phonton interference without bunching two photons

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Abstract: We report a quantum interference experiment in which the two-photon entangled state interference cannot be pictured in terms of the overlap and bunching of two individual photons on a beamsplitter.

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Among many different two-photon interference effects in spontaneous parametric down-conversion (SPDC) field, the observation of null 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, has attracted a lot of attention [1]. The two-photon interference, in this case, 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. As a result, it has been commonly understood that two photons must overlap at the beamsplitter to exhibit such a two-photon interference effect.

Is the overlap of the two photons indeed necessary for interference? Pittman *et. al.* first reported an experiment which dealt with this question [2]. In their experiment, however, the pump photon must have coherence time much bigger than the delay introduced between the photon pair to observe any interference. 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 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 explanation of general two-photon interference 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). We also present an experiment in which the SPDC photons do overlap at the beamsplitter, but interference does not (and cannot) occur.

The basic idea of the experiment can be seen in Fig. 1 [3]. The photon pair is generated from a 3 mm thick type-II BBO crystal, pumped by an ultrafast laser pulse with coherence time of approximately 130 fsec. The pump pulse has the central wavelength of 390 nm and the wavelengths of the SPDC photons are centered at 780 nm. 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). Each photon then passes through a 21.2 mm long quartz rod, QR1 and QR2, (slow axes are vertically oriented) which generates a relative group delay of 668 fsec between the two photons. This delay is much bigger than the pump pulse duration as well as the 100 fsec single-photon wavepacket determined by the 20 nm spectral filters inserted in front of the detectors. An additional half-wave plate and the polarization beamsplitter (PBS) complete the interferometer. Photon pairs are then detected by two single-photon counting modules (D1 and D2) after passing through polarizers (A1 and A2).

The experimental data for this case are shown in Fig. 1. The measurement were made for two different polarizer settings: A1/A2 = $45°/45°$ and $45°/-45°$. High-visibility quantum interference is apparent from the data and the visibility is higher than the classical limit (50%) as well as the limit for the Bell-inequality violation (71%). This clearly establishes that the observed interference is of quantum origin.

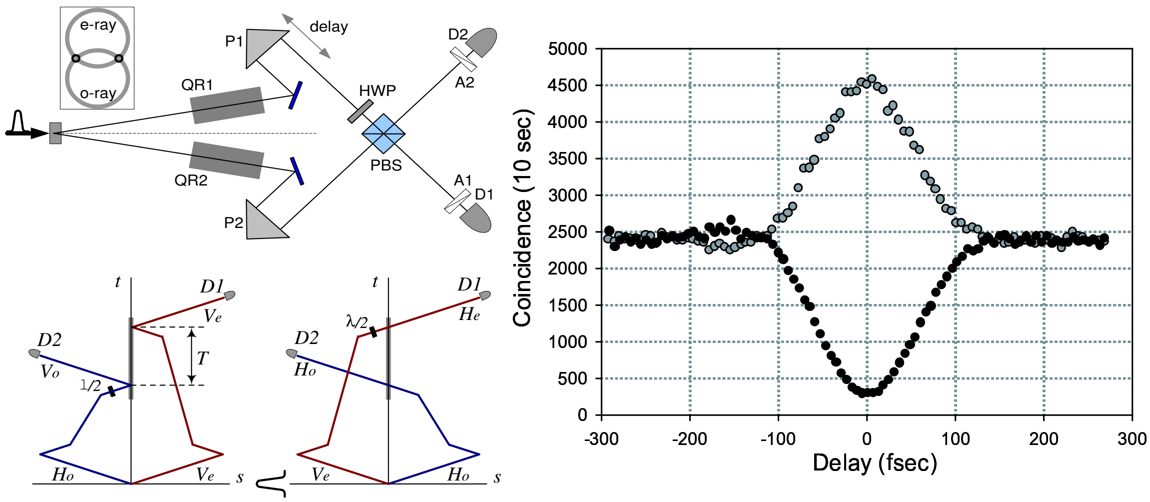

Fig. 1. Experimental setup and data. Experimental data show 87% visibility. Lower left figures show the two-photon Feynman amplitudes for the current experiment. Even though photons do not overlap at the polarizing beamsplitter, the resulting two-photon amplitudes are indistinguishable.

Let us now discuss the case in which the photons do overlap at the (polarizing) beamsplitter but interference does not and cannot occur. To make the photons overlap at PBS, the optic axes of the quartz rods were orthogonally oriented, i.e, QR1 = V and QR2 = H. In this case, the photon pair accumulates the same group delay when passing the quartz rods so that they will overlap, in time, at PBS. Even though individual photons do overlap at the beamsplitter PBS, the two Feynman alternatives, shown in Fig. 1, have now become distinguishable in time [3]. As a result, quantum interference should disappear and this has been confirmed experimentally. This disappearance of quantum interference can be traced back to the 'clock' effect of the pump pulse, which put time tags on the quantum mechanical amplitudes.

Finally, we note that the interferometer discussed in this work may be useful for studying decoherence management using linear optical elements (wave plates, polarizing beam splitters, etc.) in entangled two-qubit systems, as we observe near complete restoration of quantum interference, hence polarization entanglement, even after the original qubit pairs (which are in mixed states) went thorough decoherence introducing birefringent elements.

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References

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