Quantum interference of distinguishable photons

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Abstract: In usual quantum interference experiments, which involve different polarization states of photons, the polarization information of the photons should be "erased" to observe interference of any kind. Here we report a counter-intuitive quantum interference effect in which polarization states of photons do not play any role in interference.

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Interference of a quantum mechanical particle is observed when an event can occur by any of several alternate pathways. If an experiment is performed in which it is possible to determine which of the alternate pathways was actually taken, then the interference is lost. This principle applies classical interference effects, for example, Michelson interference effect, as well as quantum interference effects, such as two-photon quantum interference effects. For example, consider the two-photon anticorrelation experiment demonstrated in Ref. [1]. If the two photons have the same polarizations and overlap at the beamsplitter, quantum interference occurs. Quantum interference disappears, however, the photons have the orthogonal polarization, which provides the distinguishing information. If one can somehow "erase" this distinguishing polarization information, it is possible to recover interference, for example, by using properly oriented polarizers.

Here, we report a quantum interference experiment in which the detected photons retain their distinguishing information. The photons approach the beamsplitter at different times, with different polarizations, and may even have different wavelengths. They propagate directly to the detectors without passing through compensating elements and retain their distinguishing properties until being absorbed by the detectors. Nonetheless, quantum interference is observed in the joint detection rate of the two detectors.

An outline of the experimental setup is shown in Fig. 1. A 3 mm thick type-II BBO crystal is pumped by a train of ultrafast pulses with central wavelength of 390 nm and pulse duration of approximately 120 fsec. Orthogonally polarized spontaneous parametric down-conversion photon pair, signal and idler photons, have the center wavelengths of 780 nm. The photons are emitted into two distinct cones, one corresponding to the e-ray (V-polarized) and the other to the o-ray (H-polarized) of the crystal. Here we are interested in the intersections of the two light cones, where the polarizations of the single photons cannot be defined. These two directions, defined by a set of apertures, make an angle of ± 3 degrees with respect to the pump propagation direction. These two spatial modes are directed by mirrors to the two input ports of an ordinary non-polarizing beamsplitter. The output ports are monitored by single-photon counting detectors. Broadband (20 nm) spectral filters preceding the detectors help to reduce background counts.

A set of quartz rods and quartz plates are inserted in each arm of the interferometer: QR1 and QR2 are 20 mm long quartz rods and QP1 and QP2 are 600 μm thick quartz plates. With their optic axes vertically, these birefringent elements introduce a group delay of roughly 668 fsec between the V- and H-polarized photons. By tilting the quartz plates QP2 about their optic axes, it is possible to introduce an additional fine delay between the orthogonally polarized photons. The delay between the two arms of the interferometer is controlled by a trombone prism which is attached to a computer controlled DC motor. The count rates of two detectors, as well as the rate of coincidences, were recorded as a function of the delay between the two arms of the interferometer. The effective coincidence window used in this experiment was about 3 nsec which is smaller than the pump pulse repetition period ($\approx$ 13 nsec). Note that unlike usual two-photon state experiments, polarizers are not used in this experiment.

Quantum interference is observed as the delay between the two arms is adjusted. This can be seen as the peak and dip shown in Fig. 1. Although a thick crystal is used with ultrafast pumping pulse, high visibility ($\sim$ 93%) quantum interference is observed in coincidence. The two different data sets correspond to two different phase settings, i.e., two different orientations of the quartz plates QP2. Tilting the quartz plates introduces a sub-wavelength delay between the orthogonally polarized modes in the lower arm. The peak-dip phase is associated with this additional birefringent delay. Tilting the quartz plates increases not only the relative delay, but also the total path length for the two different polarizations. This is reflected as an offset between the peak and dip.

We note here that the photon pair approaches the beamsplitter with very different properties: they are orthogonally polarized and approach at different times (the photon pair does not overlap at the beamsplitter). It is somewhat surprising, then, that high visibility interference is observed even though the photons' properties are not altered before the detection process, i.e., no elements are introduced after the beamsplitter to mask the distinguishing information. To emphasize the fact that the quantum interference is achieved with distinguishable photons, the experiment was repeated with polarizers placed in front of the detectors. One of the polarizers was aligned to pass horizontally polarized light, while the other was aligned to pass vertically polarized light. The only photons that may be detected in such a set-up are emitted with orthogonal polarizations, approach the beamsplitter with orthogonal polarizations, and are detected with orthogonal polarizations. Nevertheless, quantum interference with similar visibility is observed (not shown). The only difference was the reduction of the overall count rate and the interference peak and dip features are the same as the one shown in Fig. 1.

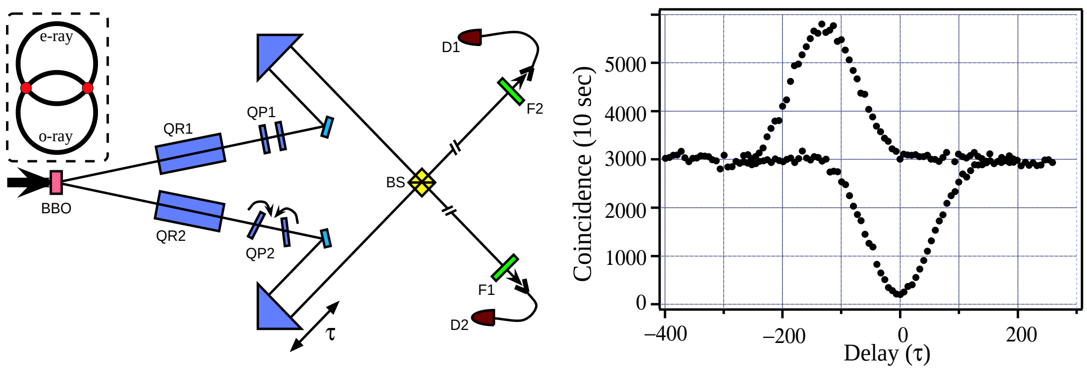

Fig. 1. Experimental setup and data. Note that no polarizers are used before detectors. The peak-dip visibillity of the data is about 93%.

The experimental results show that interference may be observed, even when the detected photons differ in their polarizations and their arrival times. Calculations show that similar results may be obtained when the photons also differ in their wavelengths. The present experiment, however, shows that the effect persists in the presence of spectral distinguishability. It is well established that the photons emitted by a type-II crystal pumped by an ultrafast laser carry distinguishing spectral information. The photons may have identical center wavelengths, but because of the different dispersive properties for the two polarizations, the bandwidths are generally different. This leads to reduced visibility in many experiments employing this type of source, unless narrow spectral filters are placed before the detectors (essentially masking the distinguishing spectral information). The photons generated in the present experiment carry the same type of distinguishing spectral information. (The 20 nm filters are too broad to remove this information.) Even so, the visibility is much higher than would be expected if this spectral information were to play a role.

This counterintuitive result can be understood as the interference and indistinguishability between two two-photon or biphoton wavepackets and is discussed in detail elsewhere [2].

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