Direct observation of photon pairs at a single output port of a beam-splitter interferometer

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Quantum theory predicts that two indistinguishable photons incident on a beam-splitter interferometer exit together (the pair emerges randomly from one port or the other). We use a special photon-number-resolving energy detector for a direct observation of this quantum-interference phenomenon. Simultaneous measurements from two such detectors, one at each beam-splitter-interferometer output port, confirm the absence of cross coincidences. Photon-number-resolving detectors are expected to find use in other quantum-optics and quantum-information-processing experiments.

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INTRODUCTION

The seminal experiment carried out by Hong, Ou, and Mandel some 15 years ago [1] is one of the most important in the annals of quantum optics. This experiment demonstrated that two indistinguishable photons, incident on the two ports of a simple beam splitter, interfere in such a way as to always emerge as a pair, exiting randomly from one port *or* the other. They could only observe this phenomenon indirectly, however, since traditional single-photon-counting detectors cannot register more than one photon within the dead-time period of the device. Hong, Ou, and Mandel circumvented this technical limitation by designing an experiment in which they measured the complement of what they sought to observe. They used two single-photon-counting detectors, placing one at each output port of the beam splitter, and then searched for cross coincidences between the two detector outputs. Finding none, they inferred that the two photons do not exit from different ports of the beam splitter. Based on this ''test of exclusion,'' and energy conservation, they deduced that both photons must exit via the same port of the device. There have been many variations on this original theme based on the same test of exclusion [2–5]. Excess photon pairs have been previously observed, but only via indirect measurements in experiments involving multiple beam splitters and multiple single-photon detectors [6,7], and in the indirect effect of photon pairs on single-photon detector rates [8].

We have carried out a polarization version of the Hong-Ou-Mandel experiment and report the direct observation of photon coincidences at a single output port of the interferometer. What makes this possible is a unique energy detector [9] that has the capability of registering the *number* of photons impinging on it. Our experimental results are in accord with the quantum theory of photon interference in a beam-splitter interferometer [10–13].

We have also made measurements at both output ports of the beam-splitter interferometer using two such detectors. This has permitted us to demonstrate the enhancement of coincidences at a single output port concomitantly with the diminution of cross coincidences at the two output ports. We thus simultaneously conduct two experiments: a single-output-port photon coincidence measurement and the original photon cross-coincidence measurement. Our observations confirm the inferences made by Hong, Ou, and Mandel [1] and Shih and Sergienko [14].

EXPERIMENT

The experimental arrangement, shown in Fig. 1, is similar to that used in related quantum-interference experiments

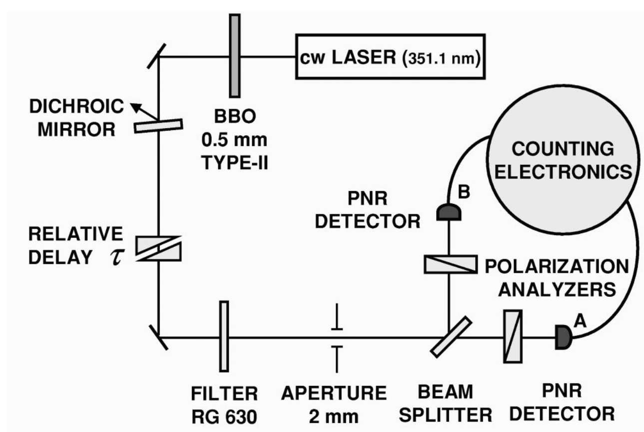

FIG. 1. Schematic of the polarization-based analog of the Hong-Ou-Mandel interference experiment using type-II collinear degenerate spontaneous parametric down-conversion. Photon-number resolving (PNR) detectors permit the direct observation of photon coincidences at a single output port of the beam-splitter interferometer as well as cross coincidences at the two output ports.

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[15], but photon-number resolving (PNR) transition-edge sensors [9] replace the usual photon-counting avalanche photodiodes.

To generate orthogonally polarized photon pairs, a single-line 351.1-nm continuous-wave (cw) argon-ion laser operated at 100 mW was used to pump a 0.5-mm-thick β-BaB_2O_4 (BBO) nonlinear-optical crystal, aligned for type-II collinear degenerate spontaneous parametric down-conversion (SPDC). The low power of the pump ensures that the photon pairs are well separated in time. A 2-mm aperture placed 70 cm beyond the crystal was used to select only those photon pairs that propagate collinearly with the pump. The pump is disposed of by use of a dichroic mirror and a RG-630 colored glass filter.

At the heart of the interferometer is a nonpolarizing beam splitter that distributes the photon pairs into two spatial modes, denoted A and B in Fig. 1. In each arm, a Glan-Thompson polarization analyzer oriented at 45° with respect to the x direction (which is defined by the o-ray polarization plane of the BBO crystal in a right-handed coordinate system with respect to the wave vector as the positive z direction) renders the two photons indistinguishable in polarization. Narrow-band interference filters were not used in the experiment.

A lens in each arm (not shown) couples the light into two 9-μm mode-field-diameter optical fibers, each of which is connected to a separate PNR detector operated in a cryostat. Detection events from the two PNR detectors were recorded and analyzed using a computer-controlled system that registers time-stamped single- and double-photon events. Software is used to extract the coincidences at a single detector and the cross coincidences from the two detectors.

The detector elements of the transition-edge sensor are photolithographically patterned 40-nm-thick tungsten thin films deposited on a silicon substrate [9]. The substrate is cooled to approximately 60 mK, about half the superconducting-to-normal transition temperature of 100 mK (the transition width is about 1 mK). A bias voltage across the thin film maintains the temperature in the transition region via Joule heating. An incident photon absorbed by the tungsten film is converted to a photoelectron, which raises the electron temperature of the film, thereby increasing its resistance. The time integral of the associated decrease in current, multiplied by the bias voltage, provides the total photoelectric energy absorbed by the thin film within its 15-μsec thermal relaxation time. In conducting an optical experiment using light of a specified wavelength, the number of photons incident within the thermal relaxation time is determined by establishing the total energy transferred to the detector within this time. Of course, energy detectors of this kind cannot distinguish between the absorption of two photons, each of energy E, and the absorption of a single photon of energy $2E$; great care was therefore used to prevent UV pump photons from leaking through to the detectors.

The typical full-width half-maximum energy resolution of these detectors is currently about 0.25 eV at 1.77 eV, corresponding to 100 nm at a central wavelength of 700 nm. Over the range of wavelengths of interest in our experiments, the quantum efficiency of these PNR detectors is approximately

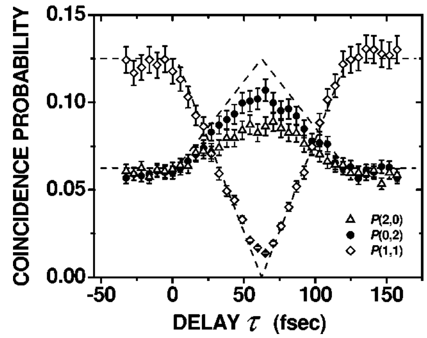

FIG. 2. Experimental coincidence probabilities $P(2,0)$ and $P(0,2)$, and cross-coincidence probability $P(1,1)$, as a function of the relative delay time between the photons τ imparted by the compensator (symbols). The theoretical curves (dashed) are computed from the ideal single-mode theory provided in Eqs. (3) and (4), using the state function given in Eq. (2), and assuming a crystal of length 0.5 mm. The data follow the trends of the theory well, but with reduced visibility resulting from imperfect alignment and asymmetric polarization losses in the system.

20% [16], as determined via an absolute measurement technique [17–19]. The signal is read out of the detector using a system that incorporates an array of dc superconducting quantum-interference devices (SQUIDs), which operate as current-sensitive amplifiers. To limit spurious ''pileup'' counts, experiments are carried out using a reduced singles counting rate ~1000 counts/sec, an order of magnitude lower than the achievable counting rate.

A Babinet-type compensator consisting of two parallel quartz prisms and a fixed quartz plate, z cut to eliminate transverse birefringence, is used to modify the relative time delay τ between the two photons. An experiment is conducted by modifying the degree of distinguishability (achieved by varying the delay time τ over a range of hundreds of femtoseconds) and tracing out three curves: the coincidence probability at detector A, denoted $P(2,0)$; the coincidence probability at detector B, denoted $P(0,2)$; and the cross coincidence probability, denoted $P(1,1)$.

The results of a typical experiment are illustrated in Fig. 2. The numerical values of the coincidence probabilities are obtained as follows. Five data rates are measured in an experiment conducted at a large delay time, corresponding to the shoulders of the interference pattern: singles and coincidences at each of the two detectors, and cross coincidences. These five measured rates are used to estimate three unknown quantities: the overall efficiency for registering an event at detector A for a single photon at the source, the same for detector B, and the rate of photon pairs emitted by the source. This enables us to compute the normalized form for the coincidence probabilities presented in Fig. 2.

Never before directly seen are the data for the peaks in the coincidence probabilities, $P(2,0)$ and $P(0,2)$, at detectors A and B, respectively. These peaks are a manifestation of excess photon pairs at a single output port of the beam-splitter interferometer. The data points for the relationship between the complementary cross-coincidence probability $P(1,1)$ (diamonds) were obtained concomitantly; they exhibit the familiar dip associated with the quantum interference of indistinguishable photons [15].

Delay times τ that are substantially larger, or smaller, than those at the dip/peak correspond to distinguishable photons. In that domain the coincidence probabilities are characterized by classical particlelike statistics, namely, the binomial counting distribution [12]. The cross-coincidence probability is then expected to be twice the coincidence probability, which is, in fact, exactly what is observed on the shoulders of the interference pattern (see Fig. 2).

THEORY

For collinear SPDC confined to a single spatial mode, the quantum state at the output of the nonlinear crystal driven by a monochromatic plane-wave pump at frequency ω_p is [15]

$$|\psi\rangle = \int d\omega\, \tilde{\Phi}(\omega) \hat{a}_o^\dagger\left(\frac{\omega_p}{2}+\omega\right)\hat{a}_e^\dagger\left(\frac{\omega_p}{2}-\omega\right)|0\rangle, \quad (1)$$

where the operators $\hat{a}_o^\dagger(\omega)$ and $\hat{a}_e^\dagger(\omega)$ create photons of ordinary and extraordinary polarization, respectively, in frequency mode ω, and the limits on the integral stretch from $-\infty$ to ∞. The form assumed by the state function $\tilde{\Phi}(\omega)$, which is normalized according to $\int d\omega |\tilde{\Phi}(\omega)|^2 = 1$, depends on the physical structure of the down-conversion source. The state function for a single bulk crystal of length L is, for example, given by [15]

$$\tilde{\Phi}(\omega) \propto L \,\mathrm{sinc}\left[\frac{L}{2}\Delta(\omega)\right] e^{iL\Delta(\omega)/2}, \quad (2)$$

where the wave-vector mismatch function $\Delta(\omega) = k_p(\omega_p) - k_o(\omega_p/2+\omega) - k_e(\omega_p/2-\omega)$ depends on the dispersive properties of the birefringent medium ($k_{\{p,o,e\}}$ represent the wave numbers of the pump, ordinary wave, and extraordinary wave in the crystal, respectively) and $\mathrm{sinc}x = (\sin x)/x$.

Assuming an ideal optical system and perfect components, the coincidence probabilities, as a function of τ, are then given by

$$P(2,0) = P(0,2) = \frac{1}{32}\int dt\, |\Phi(t-\tau) + \Phi(-t-\tau)|^2, \quad (3)$$

where $\Phi(t)$ is the inverse Fourier transform of $\tilde{\Phi}(\omega)$; the integration can be extended from $-\infty$ to ∞ since the integrand is narrow in comparison with the detection window. Similarly, the cross-coincidence probability becomes [20]

$$P(1,1) = \frac{1}{16}\int dt |\Phi(t-\tau) - \Phi(-t-\tau)|^2. \quad (4)$$

The fractional prefactors in Eqs. (3) and (4), 1/32 and 1/16, respectively, can be traced to the fact that the polarization analyzers in each arm of the interferometer transmit only half the photons.

For a value of τ chosen such that $\Phi(t-\tau) = \Phi(-t-\tau)$, Eq. (3) becomes $P(2,0) = P(0,2) = 2^2/32 = 1/8$ while Eq. (4) becomes $P(1,1) = 0$, and the result reduces to the ideal boson counting distribution. In the opposite limit, when the relative delay time τ is sufficiently large, the integrals in Eqs. (3) and (4) are both equal to 2, whereupon the classical binomial counting distribution emerges: $P(2,0) = P(0,2) = 1/16$ and $P(1,1) = 1/8$.

More generally, Eqs. (3) and (4) can be combined to provide a relationship between the coincidence and cross-coincidence probabilities for arbitrary values of τ,

$$P(1,1) + P(2,0) + P(0,2) = \tfrac{1}{4}. \quad (5)$$

In particular, when the state function in Eq. (2) is used in Eqs. (3) and (4), assuming a cw pump field and a linear approximation for $\Delta(\omega)$, the cross-coincidence probability $P(1,1)$, as a function of τ, takes the familiar form of a triangular dip [14,15] while the coincidence probabilities $P(2,0)$ and $P(0,2)$ behave as triangular peaks.

The theoretical results for this ideal single-mode theory are shown as the dashed curves in Fig. 2. The data follow the trends of the theory well, although the visibilities of the quantum-interference patterns are reduced below their ideal values as a result of imperfect alignment and asymmetric polarization losses in the optical components.

CONCLUSION

We have used special photon-number-resolving energy detectors to directly demonstrate that two indistinguishable photons incident on a polarization analog of the Hong-Ou-Mandel interferometer exit the beam-splitter interferometer ports together. The absence of cross coincidences has also been concomitantly demonstrated. Our observations are in accord with the quantum-optical theory of interference in a beam-splitter interferometer. It is expected that similar results would be observed for a noncollinear configuration.

As a final note we point out that PNR detectors, such as those used here, are expected to find use in other quantum-optics and quantum-information-processing experiments. Unlike their avalanche photodiode counterparts, they could play a role in carrying out conclusive tests of local realism using a beam-splitter interferometer experiment [21]. They have already been found to be useful in a number of other important applications [22].

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