Two-Photon Interference in a Mach-Zehnder Interferometer

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Pairs of 826.8-nm correlated photons, generated by parametrically down-converting 413.4-nm krypton-ion laser light, are directed into a single Mach-Zehnder interferometer such that each photon of the pair enters a different input port. The rate of coincidence at the two output ports displays oscillations (as the path-length difference is swept) with a spatial period equal to the 413-nm wavelength of the pump photons, and with a visibility of 62% when the path-length difference exceeds the coherence length of the individual photon beams. This unequivocally demonstrates the nonclassical and entangled nature of the two-photon state.

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When single photons are incident at only one input port of an interferometer, the rate of photodetections at either of its output ports oscillates as the path-length difference of the device is swept.[1] The visibility of this second-order interference pattern decays to zero when the interferometer path-length difference exceeds the coherence length of the photons, at which point only the classical particlelike nature of light is exhibited and the input photons are detected randomly at either output port.

Fourth-order interference effects arise when pairs of photons enter one (or more) interferometers and the coincidence rate is monitored at the output ports.[2] Recent experiments with correlated photons produced in parametric down-conversion fed into Michelson interferometers have shown fourth-order interference fringes with visibilities at or below 50% for path-length differences extending beyond the coherence length.[3,4] An experiment in which photon pairs from an atomic cascade are injected into separated Mach-Zehnder interferometers has been proposed[5] as a test of Bell's inequality without involving spin or polarization, given a fringe visibility greater than 71%. Similar spin-free violations of local realistic theories have recently been predicted[6] and demonstrated[7] in experiments that exploit the phase-matching conditions of parametric down-conversion to create two-color photon pairs and superpose the differently colored photons at spatially separated beam splitters.

We report an experiment in which a stream of 826.8-nm photon pairs, obtained from the parametric down-conversion of 413.4-nm krypton-ion laser light in KD*P (deuterated potassium dihydrogen phosphate), are directed into the input ports of a *single* Mach-Zehnder interferometer. We observe nonclassical oscillations in the coincidence rate with a visibility of 62% for path-length differences both smaller and greater than the single-photon coherence length. Our observations demonstrate the entangled nature of the two-photon state produced in parametric down-conversion.

The joint state $|\Psi\rangle$ for each photon pair at the output of the parametric down-converter (the input to the interferometer) may be represented by[8,9]

$$|\Psi\rangle=\int_0^\infty\int_0^\infty \zeta(\omega,\omega')|1_\omega\rangle|1_{\omega'}\rangle d\omega\, d\omega' , \qquad (1)$$

where $|1_\omega\rangle$ and $|1_{\omega'}\rangle$ represent monochromatic single-photon states at the frequencies ω and ω', respectively (such that $\omega+\omega'\approx\omega_p$, the angular frequency of the pump photons), and $\zeta(\omega,\omega')$ is a joint spectral amplitude.

Choosing a Gaussian form for $\zeta(\omega,\omega')$ leads to relatively simple expressions for the probability of coincidence at the output of the interferometer. When the photons are coincident at the input ports, the probability of coincidence $P(1,1)$ at the output ports is[9]

$$P(1,1)=\tfrac{1}{2}+\tfrac{1}{4}V_{\rm MZ}\left[1+\exp\left(-\frac{\omega_d^2}{8\sigma^2}\right)\right]\cos(\omega_p\tau_{\rm MZ})+\tfrac{1}{4}V_{\rm MZ}\exp(-2\sigma^2\tau_{\rm MZ}^2)\left[\cos(\omega_d\tau_{\rm MZ})-\exp\left(-\frac{\omega_d^2}{8\sigma^2}\right)\right], \qquad (2)$$

where ω_d represents the magnitude of the difference between the center frequencies of the spectra of the two input photons (which is determined by the geometry of the experimental arrangement), σ represents the widths of the spectra,

τ_{MZ} is the path-length time difference between the legs of the interferometer, and the constant V_{MZ} has been included to account for experimental spatial misalignments within the interferometer. This expression predicts cosinusoidal oscillations at the pump frequency ω_p as the time difference τ_{MZ} is scanned. For the degenerate case in a perfectly aligned Mach-Zehnder interferometer ($\omega_d=0$, $V_{MZ}=1.0$), these oscillations are permitted to exhibit maximal visibility

$$V \equiv \frac{P(1,1)_{\max}-P(1,1)_{\min}}{P(1,1)_{\max}+P(1,1)_{\min}}=100\%\,, \tag{3}$$

and are independent of the coherence time $t_c \equiv 1/\sigma$ of the individual photon beams.[9]

When the photons arrive at the input ports of the interferometer with a path-length time difference τ_{IN} that is larger than the coherence time t_c [rather than with $\tau_{IN}=0$ as considered in Eq. (2)], the output coincidence probability is given by the expression[9]

$$P(1,1)=\tfrac{1}{2}+\tfrac{1}{4}V_{MZ}\cos(\omega_p\tau_{MZ}) + \tfrac{1}{4}V_{MZ}\exp(-2\sigma^2\tau_{MZ}^2)\cos(\omega_d\tau_{MZ})\,. \tag{4}$$

For a perfectly aligned interferometer ($V_{MZ}=1.0$), Eq. (4) predicts oscillations with a visibility of 33% for small values of τ_{MZ} and a visibility that can become no greater than 50% for arbitrarily large values of τ_{MZ}. In principle, each photon of the pair is now completely time separated from its partner as it traverses the interferometer. In this case the experiment is analogous to that conceived by Franson[5] in which pairs of photons are presented to two identical but space-separated Mach-Zehnder interferometers whose path-length time differences are much smaller than the coincidence gate time.

In principle, apertures selecting the down-converted photons may be aligned so that the spectra of the selected photons have the same center frequencies ($\omega_d=0$); however, perfectly degenerate parametric down-conversion is rarely achievable in the laboratory because of imperfect aperture alignment. The degree of nondegeneracy ω_d, and the spectral width σ, can be determined by measuring the coincidence probability $P(1,1)$ at the output ports of the first 50/50 beam splitter of the interferometer, as a function of the path-length time difference τ_{IN} from the down-converter output to the interferometer input,[8-10]

$$P(1,1)=\tfrac{1}{2}[1-\exp(-\omega_d^2/8\sigma^2)\exp(-2\sigma^2\tau_{IN}^2)]\,, \tag{5}$$

when each of the photons enters a different input port of the device. It is clear from Eq. (5) that $P(1,1)$ may dip all the way to zero only in the degenerate case ($\omega_d=0$) and when the photons' path-length times are equal ($\tau_{IN}=0$).

Using correlated photons from a parametric down-converter, we have measured ω_d and the spectral width of the photons σ at the output of a single beam splitter [Eq. (5)], and we have examined the coincidence rate at the output of the interferometer in the regimes $\tau_{IN}=0$ [Eq. (2)] and $\tau_{IN}>t_c$ [Eq. (4)]. A schematic diagram of the experimental setup is shown in Fig. 1. The 413.4-nm line of a Coherent Model K3000 krypton-ion laser was focused by a 1-m focal-length lens onto a 15-mm-long KD*P type-I phase-matched crystal at 90° incidence to the optic axis. For degenerate down-conversion, photons at 826.8 nm emerge from the crystal symmetrically in a cone of angle $\approx 14°$ about the pump beam. Two 2.5-mm-diam apertures are used to select nearly degenerate photons. The photons are directed by mirrors onto a beam-splitter cube (BS1), and then redirected onto a lower portion of the same beam-splitter cube (schematically shown as BS2) by two right-angle prisms, thus forming a folded Mach-Zehnder interferometer. The beam-splitter cube and prisms are mounted together as a unit on a translation stage. The position of the entire unit determines τ_{IN}. The distance between one of the prisms and the beam-splitter cube can be adjusted within the unit by a combined micrometer and piezoelectric positioner to introduce an adjustable path-length difference time delay τ_{MZ} between the arms of the interferometer. The photons at the output ports of the interferometer are then focused by two lenses onto two Si avalanche photodiodes (DET1 and DET2) operated in the passively quenched Geiger mode.[11] After appropriate discrimination, amplification, and shaping, the outputs of the photodiodes are fed into a Malvern-type K7026 digital correlator that provides the coincidence rate (COINC) and the individual count rates. A Hewlett-Packard-type HP320 computer controls the experiment and collects the data.

The single-beam-splitter coincidence rate specified in Eq. (5) can be measured in our setup by blocking one arm of the interferometer.[10] In doing this we measured the $1/e^2$ width of the photons' spectra to be $ct_c=26.2$ μm so that t_c was determined to be 87 fsec, giving $\sigma=1/t_c=1.14\times10^{13}$ sec^{-1}. For ideal spectral overlap of the photons ($\omega_d=0$) and ideal 50/50 beam splitters we would expect a complete cancellation of the coincidence probability. If it is assumed that the incomplete cancel-

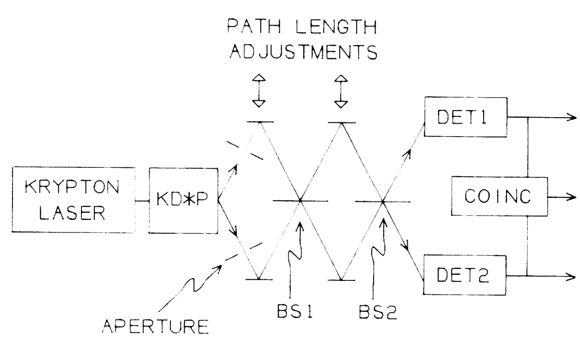

FIG. 1. Schematic diagram of the experimental setup.

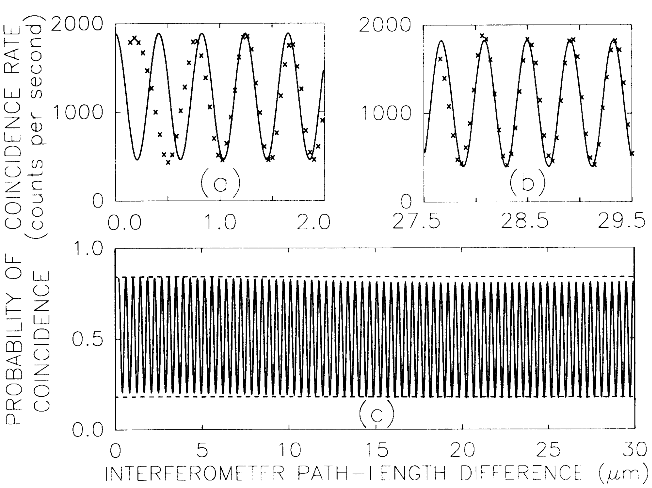

FIG. 2. The coincidence rate in counts per second (cps) is plotted against the interferometer path-length difference τ_{MZ} (μm) for photons coincident at the inputs to the Mach-Zehnder interferometer ($c\tau_{IN}=0$). The solid curves represent Eq. (2) with $\omega_d=1.18\times10^{13}$ sec^{-1}, $V_{MZ}=0.675$, $\sigma=1.14\times10^{13}$ sec^{-1}, and $\omega_p=4.56\times10^{15}$ sec^{-1}. $P(1,1)=1.0$ corresponds to 2257 cps. (a) Small path-length difference $c\tau_{MZ}\sim1$ μm; (b) large path-length difference $c\tau_{MZ}\sim28$ μm; (c) Eq. (2) plotted over the entire range from $c\tau_{MZ}=0$ to 30 μm.

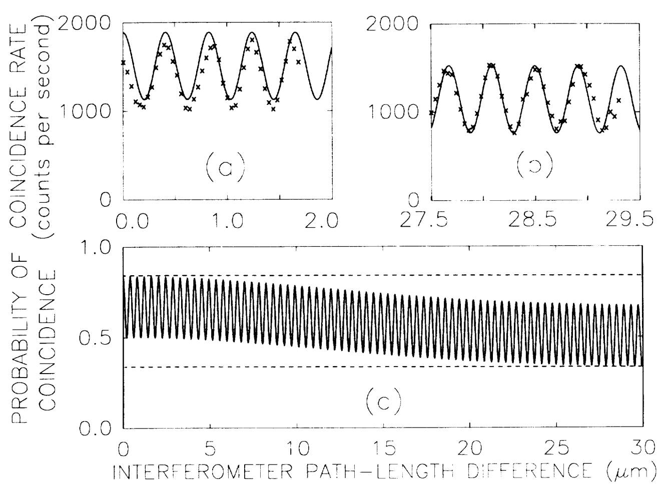

FIG. 3. The coincidence rate in counts per second (cps) is plotted against the interferometer path-length difference (μm) for photons separated by $c\tau_{IN}=100$ μm at the inputs to the Mach-Zehnder interferometer. The solid curves represent Eq. (4) with $\omega_d=1.18\times10^{13}$ sec^{-1}, $V_{MZ}=0.675$, $\sigma=1.14\times10^{13}$ sec^{-1}, and $\omega_p=4.56\times10^{15}$ sec^{-1}. $P(1,1)=1.0$ corresponds to 2257 cps. (a) Small path-length difference $c\tau_{MZ}\sim1$ μm; (b) large path-length difference $c\tau_{MZ}\sim28$ μm; (c) Eq. (4) plotted over the entire range from $c\tau_{MZ}=0$ to 30 μm.

lation we observed (87%) is entirely due to the lack of frequency overlap (our beam splitters are close to 50/50), we obtain $\omega_d=1.18\times10^{13}$ sec^{-1}. This corresponds to a wavelength mismatch of about 4 nm from degeneracy in the center frequencies of the spectra of the photons selected by the apertures.

The results of two scans of τ_{MZ} around path-length differences near 0 and 28 μm are shown in Figs. 2(a) and 2(b), respectively. The beam-splitter-prism unit is at the $\tau_{IN}=0$ position (coincident photons at the input ports); hence, we expect Eq. (2) to hold as plotted in Fig. 2(c). In accord with the theory, oscillations in the coincidence rate are seen to occur with a spatial period equal to the 413-nm wavelength of the pump photons. The experimental visibility is 62%. The theoretical visibility from Eq. (2), assuming perfect spatial alignment in the interferometer ($V_{MZ}=1$) and using the value of ω_d determined from the single-beam-splitter results ($\omega_d=1.18\times10^{13}$ sec^{-1}), is 87%. Using a value of $V_{MZ}=0.675$ and the value of ω_d obtained from the single-beam-splitter result gives the solid curves in Fig. 2, which have the same visibility as the experimental data. It is clear from Fig. 2 that the oscillations in the coincidence rate occur over path-length differences that exceed the coherence length of the photons. This is a manifestation of the correlated or entangled nature of the two-photon state created in the down-conversion process. The deviation of the data points from pure sinusoidal behavior likely arises from mechanical instabilities in the apparatus.

The oscillations are expected to disappear when the path-length difference in the interferometer exceeds the coherence length of the pump beam. For independent input photons, however, the visibility of the oscillations would decay to zero for path-length differences that exceeded the coherence length of either photon.[9]

To verify the 50% upper limit on the visibility for nonoverlapping input photons we moved the beam-splitter-prism unit 100 μm ($\tau_{IN}\sim330$ fsec) so that the photons were not coincident at the beam splitter BS1 in Fig. 1, and we scanned the path-length difference time τ_{MZ}. The solid curves presented in Fig. 3 represent Eq. (4) using $\omega_d=1.18\times10^{13}$ sec^{-1} and $V_{MZ}=0.675$, as determined above. We again observe oscillations at the pump frequency. For small values of τ_{MZ} the visibility is 28% as shown in Fig. 3(a), in good agreement with the 33% visibility predicted by Eq. (4). The visibility increased to 33% when the interferometer path-length difference was scanned in the vicinity of $\tau_{MZ}\sim28$ μm [Fig. 3(b)], but it never exceeded 50% in accord with the theoretical prediction.

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