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Correlated two-photon interference in a dual-beam Michelson interferometer

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We report on an interference effect arising from a two-photon entangled state produced in a potassium dihydrogen phosphate (KDP) crystal pumped by an ultraviolet argon-ion laser. Two conjugate beams of signal and idler photons were injected in a parallel configuration into a single Michelson interferometer, and detected separately by two photomultipliers, while the difference in its arm lengths was slowly scanned. The coincidence rate exhibited fringes with a visibility of nearly 50%, and a period given by half the ultraviolet (not the signal or idler) wavelength, while the singles rate exhibited no fringes.

Nonlocal effects in quantum mechanics associated with *entangled states* have been the subject of much recent interest.[1,2] An important example of such states is the Einstein-Podolsky-Rosen-Bohm singlet state, which produces a violation of Bell's inequalities.[3] Franson[1] suggested that, without the use of polarizers, but by use of two spatially separated interferometers, one can observe a violation of Bell's inequalities for position and time. The meaning of this violation would be that it is fundamentally impossible to ascribe any locally objective values to the time of emission of a photon from an atom. Horne, Shimony, and Zeilinger[2] have given a general analysis of entangled states which can produce violations of Bell's inequalities, and suggested some interesting experiments to see the two-particle interference arising from these states, by use of spontaneous parametric down-conversion.[4]

Here we report on the observation of a closely related two-photon interference. Although in its present form the interference effect described below possesses a classical explanation based on stochastic noise theory, the quantum explanation is, we believe, the more fundamental one, and we present it first. Two photons are produced in the entangled state

$$|\psi\rangle_{\text{in}} = \int d\omega_s \phi(\omega_s)\,|\omega_s\rangle\,|\omega_p-\omega_s\rangle\,, \qquad (1)$$

in the process of spontaneous parametric down-conversion in a crystal with a $\chi^{(2)}$ nonlinearity excited by pump photons at frequency ω_p. Here $\phi(\omega_s)$ is the probability amplitude for production of a signal photon at ω_s. This state expresses the fact that two photons, i.e., a signal photon at frequency ω_s and an idler photon at frequency $\omega_i = \omega_p - \omega_s$, are created simultaneously, i.e., as a conjugate pair, inside the crystal from the annihilation of a single pump photon. Energy is conserved during this process:

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i\,. \qquad (2)$$

The interaction Hamiltonian is

$$H = \chi^{(2)} a_s^\dagger a_i^\dagger a_p + \text{H.a.}\,, \qquad (3)$$

where $a_{s(i)}^\dagger$ denotes the creation operator of the signal (idler) photon, and a_p the annihilation operator for the pump photon.

Note that energy conservation, Eq. (2), does not forbid the signal photon from having a broad spread in energy, and the idler photon from having a conjugately broad spread in energy, while the pump photon may have a very narrow spread in energy, such that $\Delta\omega_p \ll \Delta\omega_s, \Delta\omega_i$. In this experiment the pump photon originates in a laser; consequently, it has a negligible frequency width $\Delta\omega_p$.[5] In principle, the spread in signal and idler frequencies is limited only by phase-matching considerations, but in practice, it is usually limited by the bandwidth of the filters placed in front of the detectors.

Now consider what happens when the entangled state given by Eq. (1) enters the dual-beam Michelson interferometer shown in Fig. 1. Following Franson,[1] we restrict ourselves here to the case where the optical-path-length difference ΔL, which is *twice* the difference in lengths between the two arms of the interferometer, satisfies the inequality

$$\Delta L \gg \Delta l_s, \Delta l_i\,, \qquad (4)$$

where $\Delta l_{s(i)}$ is the coherence length of the signal (idler) photon, which is inversely related to its bandwidth. In other words, we are well outside the white-light-fringe region, so that the fringe visibility in normal, single-photon interference is essentially zero. One does not expect to see any fringes, since there is no longer any substantial overlap of a delayed photon wave packet with itself when ΔL is very large. (Here it is helpful to regard the Michelson interferometer as two optical delay lines in parallel.) In our experiment, we monitor the single-photon interference

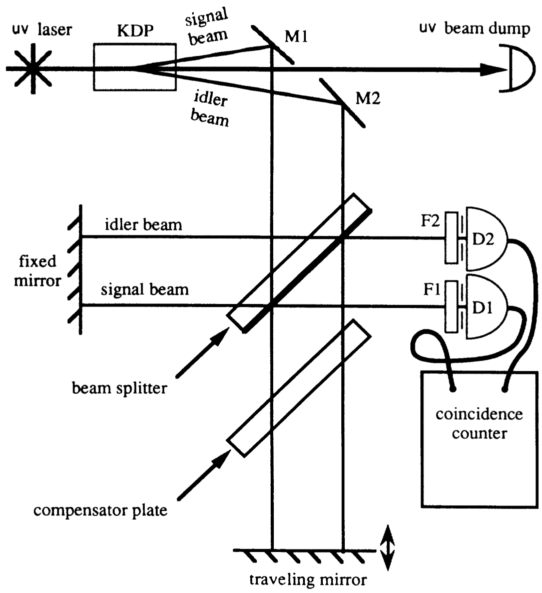

FIG. 1. Schematic of the dual-beam Michelson interferometer experiment. A uv beam from an argon-ion laser operating at 351 nm enters a KDP crystal and generates two conjugate beams of signal and idler photons, both near 702 nm. The signal and idler beams are made parallel by mirrors $M1$ and $M2$, and injected into the Michelson interferometer. Photons in the two output beams are detected either singly or in coincidence by two separate photomultipliers $D1$ and $D2$, while the traveling mirror is slowly scanned by a stepping motor.

fringes by measuring the singles count rate, i.e., the intensity of the output beams of light, while ΔL is slowly scanned.

However, *two-photon* interference fringes can be seen by counting signal and idler photons in coincidence. For ease of understanding, we present here a simplified quantum analysis of this interference effect. Elsewhere, we shall present the results of a more comprehensive analysis based on fourth-order correlation functions. When a given coincidence event occurs, we note that it is fundmentally impossible, even in principle, to tell the difference between the following two possibilities: (i) both photons went through the short arm of the interferometer, or (ii) both photons went through the long arm of the interferometer. For brevity, we call the first possibility the "short-short" one, and the second possibility the "long-long" one. The other possibilities, e.g., the "long-short" one, with one photon going along the long arm, and the other going along the short, are *distinguishable* from the above two, and do not produce coincidences if the detectors are extremely fast. According to the superposition principle, one must add the probability amplitudes of *indistinguishable* processes, and then take the absolute square to find the probability. Thus the probability amplitude for a coincidence event at time t occurring at two detectors placed at $\mathbf{r}_1$ and $\mathbf{r}_2$ is

$$\psi_{\rm out}(\mathbf{r}_1,\mathbf{r}_2;t)=\langle \mathbf{r}_1,\mathbf{r}_2;t\,|\,\psi\rangle_{\rm out}\propto 1+\exp(i\Phi)\,, \tag{5}$$

where we have assigned an amplitude 1 to the short-short process, and an amplitude $\exp(i\Phi)$ to the long-long one. Here Φ is the total extra phase accumulated by the two conjugate photons during the long-long process, relative to the short-short one. In the present case,

$$\Phi=(k_s+k_i)\Delta L=2\pi\Delta L/\lambda_p\,, \tag{6}$$

where $k_{s(i)}$ is the vacuum wave number of the signal (idler) photon, and λ_p is the uv pump wavelength. Note that it is the uv wavelength, *not* the signal or idler wavelength, which enters here, although no uv light is present inside the interferometer. Note also that since the coherence length of the uv laser can be very long, the two-photon interference fringes can have a high visibility for a correspondingly long ΔL.

The probability of coincidences, and hence the coincidence count rate R_c, is

$$R_c\propto\psi^*_{\rm out}(\mathbf{r}_1,\mathbf{r}_2;t)\,\psi_{\rm out}(\mathbf{r}_1,\mathbf{r}_2;t)\propto 2(1+\cos\Phi)\,. \tag{7}$$

However, if the post-detection (electronic) resolution time is too slow to exclude the long-short and short-long processes from the coincidence count rate, then we must add to the right-hand side of Eq. (7) a background of two due to these accidental events. This happens when the electronic resolution time τ is longer than $\Delta L/c$. As a result, the visibility of the fringes detected in coincidence is reduced to 50%. In the present experiment, this is the case, since τ is determined by the window of our coincidence counter, which is 5 ns, and since $\Delta L=240\ \mu$m. A calculation starting from Eq. (1) using the technique of fourth-order correlation functions yields the same result under these conditions.

Our experiment is different from the one suggested by Horne, Shimony, and Zeilinger[2] which was recently performed by Rarity and Tapster.[6] Whereas their experiment involves the superposition of momentum states in different *directions*, ours involves the superposition of energy states at different *times*. Also, our experiment is different from the one proposed by Franson[1] in that his involves an atomic cascade light source and two spatially separated Mach-Zehnder-type interferometers, whereas ours involves a parametric fluorescence light source and a single dual-beam Michelson interferometer.

The experimental setup is shown in Fig. 1. A 130-mW uv beam from a coherent Innova 200 argon-ion laser operating at a wavelength of 351.1 nm entered a 10-cm-long potassium dihydrogen phosphate (KDP) crystal and generated two conjugate beams of signal and idler photons around 702.2 nm, in the process of degenerate parametric fluorescence. The crystal was cut such that the optic axis was at an angle of 50.3° with respect to the end faces. The two phase-matched degenerate conjugate beams emerged at an angle of 1.5° with respect to the axis defined by the uv beam. After traversing the crystal, the uv beam was absorbed in a beam dump, and did not enter the interferometer. The signal and idler beams were made parallel to each other by means of mirrors $M1$ and $M2$, and injected side by side into a single Michelson interferometer. Upon leaving the output port of the interferometer, photons in the two parallel beams passed through filters $F1$ and $F2$ and were detected by photomultipliers $D1$ and $D2$, while the traveling mirror of the Michelson was slowly scanned by a stepping motor. We calibrated the system by counting He-Ne laser fringes, and determined that one step of the stepping motor corresponded to an average motion of 6.101 ± 0.027 nm of the traveling mirror. Each detector consisted of an RCA C31034A-02 photomultiplier tube, which was cooled to approximately $-30\,^{\circ}\mathrm{C}$. The signals from the photomultipliers were amplified and directed into a Stanford Research Systems SR 400 Gated Photon Counter. The electronic delay between the signals was adjusted to maximize the coincidence count rate for a 5-ns-wide gating window.

The results are shown in Fig. 2, where the singles count rate (upper trace) and the coincidence count rate R_c (lower trace) are plotted against the arm length difference $\Delta L/2$. These data points were taken starting with $\Delta L = 240\ \mu$m, as determined by counting the steps of the stepping motor starting from the position of the white-light fringe. The coherence lengths of the signal and idler photons were measured to be $\Delta l_s = \Delta l_i = 50\ \mu$m,[7] which are consistent with the 10-nm bandwidths of filters $F1$ and $F2$ centered at 702 nm. Thus we have satisfied Eq. (4); evidence for this lies in the fact that the visibility of the fringes in the singles count rate is quite low ($< 5\times 10^{-3}$) in this region. However, the visibility of the fringes in the coincidence count rate is quite high: $46.0\% \pm 2.2\%$ (with 90% confidence). When we account for imperfect balance of the Michelson arms (the singles visibility in the white-light-fringe region was measured to be $93.0\% \pm 1.0\%$), the corrected coincidence visibility is $52.6\% \pm 3.0\%$. This agrees, within the experimental error, with the predicted value of 50%, which was used in the calculation of the solid sinusoidal curve shown in Fig. 2. The traveling mirror moved a distance of 176.1 ± 1.0 nm from one coincidence-rate maximum to the next, which also agrees, within the experimental error, with the predicted value, viz., $\lambda_p/2 = 175.6$ nm between adjacent interference maxima.

We therefore conclude that we have indeed observed a two-photon interference in the dual-beam Michelson interferometer. However, since the observed visibility is not significantly greater than 50%, we cannot claim that this is a nonclassical effect. There exists a classical-field explanation in which the rates R_s, R_i of singles detection, and R_c of coincidence detection are ensemble averages in a stochastic classical field theory. In this theory, the wave numbers k_s and k_i are classical random variables which are subjected, however, to the constraint that $k_s + k_i = k_p$, where k_p is a nonrandom variable. Then

$$\begin{aligned} R_s &\propto \langle 1+\cos k_s \Delta L\rangle = 1\,, \\ R_i &\propto \langle 1+\cos k_i \Delta L\rangle = 1\,, \\ R_c &\propto \langle (1+\cos k_s \Delta L)(1+\cos k_i \Delta L)\rangle \\ &= \langle 1+\cos k_s \Delta L+\cos k_i \Delta L \\ &\quad + \tfrac{1}{2}\cos(k_s-k_i)\Delta L\rangle + \tfrac{1}{2}\cos(k_s+k_i)\Delta L\rangle \\ &= 1+\tfrac{1}{2}\cos k_p \Delta L\,, \end{aligned} \tag{8}$$

where

$$\langle \cos k_s \Delta L\rangle = \langle \cos k_i \Delta L\rangle = \langle \cos(k_s-k_i)\Delta L\rangle = 0\,,$$

but $\langle \cos(k_s+k_i)\Delta L\rangle = \cos k_p \Delta L$. Thus this classical theory also predicts a 50% visibility. Hence, as in Hanbury-Brown-Twiss interference, our interference effect in its present form possesses a classical explanation. However, unlike the Hanbury-Brown-Twiss case, there is a possibility of improving our experiment, so that if the visibility exceeds 50%, then a classical explanation is no longer possible. Furthermore, if the visibility were to approach 100%, then, with some auxiliary assumptions, Bell's inequalities would be violated.[1,2,8] Only then can one claim to have seen a nonlocal effect. This is the goal of a future experiment.

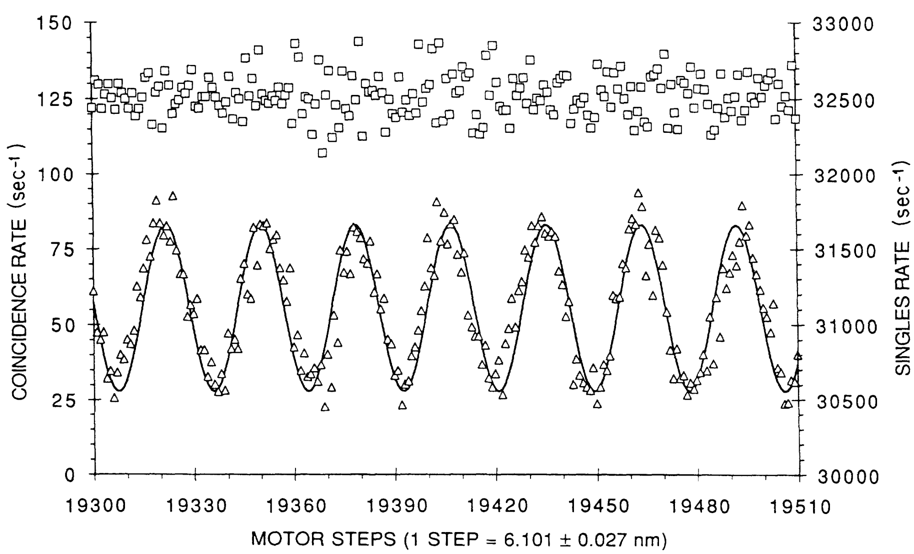

FIG. 2. Two-photon interference in the dual-beam Michelson interferometer: The coincidence count rate (left axis, triangles in lower trace) and the singles count rate (right axis, squares in upper trace) vs the arm length difference for the setup of Fig. 1. The solid line denotes the theoretical prediction (see text). These data points were taken in a region far away from the white-light fringe (with $\Delta L = 240\ \mu\mathrm{m} \gg \Delta l_s = 50\ \mu$m). The integration time per step was 1 sec.

Note added. After the submission of this paper, we found out from Professor L. Mandel that he and his group have independently performed a similar experiment and obtained similar results [see Z. Y. Ou, X. Y. Zou, L. J. Wang, and L. Mandel (unpublished)].

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[5]Specifically, the coherence length $\Delta l_p = 3$ cm of the pump photons is much longer than the path-length difference $\Delta L \leq 300$ μm of the Michelson interferometer used in our experiment.

[6]J. G. Rarity and P. R. Tapster (unpublished); see also Z. Y. Ou and L. Mandel (unpublished).

[7]The visibility of the signal (or idler) single-photon interference close to the white-light fringe was measured to have a sinclike variation with arm length difference. We determined the coherence length from the position of the first null of this pattern.

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