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Quantum interference by two temporally distinguishable pulses

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We report a two-photon interference effect, in which the entangled photon pairs are generated from two laser pulses well separated in time. In a single pump pulse case, interference effects did not occur in our experimental scheme. However, by introducing a second pump pulse delayed in time, quantum interference was then observed. The visibility of the interference fringes shows a dependence on the delay time between two laser pulses. The results are explained in terms of indistinguishability of biphoton amplitudes that originates from two temporally separated laser pulses. [S1050-2947(99)51007-X]

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The superposition principle plays the central role in interference phenomena in quantum mechanics. In a quantum-mechanical picture, interference occurs because there are indistinguishable ways for an event to occur [1]. Classically, one would not expect to observe interference from two temporally separated laser pulses. To observe interference, the two pulses, if coherent, must be brought back together in space or ''spread'' by a narrow-band filter. However, it is possible to observe interference effects for entangled two-photon states generated by two laser pulses that are well separated in time.

In this paper, we report a quantum interference experiment in which interference occurs between the amplitudes of entangled two-photon states generated by two temporally well-separated laser pulses. The delay between the two pump laser pulses is chosen to be much greater than the width of the pump pulse and the width of the ''wave packet'' determined by the spectral filter used in front of the detectors. Therefore, the ''wave packets'' are well distinguishable from the single-photon point of view. We first show why interference effects are not expected for the case of a single pump pulse in our experimental setup. Then we introduce a second pump pulse delayed in time T and show how one can recover quantum interference. In this sense, this experiment can be viewed as a temporal quantum eraser.

The two-photon state in this experiment is generated by spontaneous parametric down-conversion (SPDC). SPDC is a nonlinear optical process in which a higher energy UV pump photon is converted to a pair of lower-energy photons (usually called signal and idler) inside a noncentrosymmetric crystal (in this case, β-BaB_2O_4, called BBO), when the phase-matching condition $[\omega_p=\omega_s+\omega_i$, $\vec{k}_p=\vec{k}_s+\vec{k}_i$, where the subscripts refer to the pump (p), signal (s), and idler $(i)]$ is satisfied [2]. The signal and the idler have the same polarization in type-I SPDC, but orthogonal polarization in type-II SPDC.

Let us first consider the case in which a single pump pulse is used for a SPDC process in the experimental setup shown in Fig. 1. This two-photon interferometer works in the following way. A pair of SPDC photons is fed into the interferometer. The idler (i) is delayed by τ relative to the signal (s) before it meets the beam splitter (BS). After the BS, the signal is delayed by τ_1; however, only in one arm of the interferometer. Two analyzer-detector packages are placed at the two output ports of the interferometer. The coincidences between the two detectors are recorded to observe the fourth-order interference (second order in intensity) as well as the single counting rates of the detectors. Since we are interested in observing the fourth-order interference, we only consider the two-photon (biphoton) amplitudes that contribute to a coincidence count. There are two biphoton amplitudes that could result in coincidence counts for this interferometer: both the signal and the idler are (1) transmitted $(t$-$t)$, and (2) reflected $(r$-$r)$ at the beam splitter (BS). Notice that the r-t and the t-r amplitudes cannot result in a coincidence count, since the signal-idler photon pair ends up at the same detector (either at D_1 or D_2). If the pump is a cw (or a pulse with $\sigma_{pulse}>\tau,\tau_1$, where σ_{pulse} is the pump pulse width), interference between the amplitudes t-t and r-r may occur. Due to the long coherence length of the pump, the two biphoton amplitudes t-t and r-r may be indistinguishable, although delays τ and τ_1 are introduced as shown in Fig. 1 [3]. However, when a short pump pulse $(\tau,\tau_1>\sigma_{pulse})$ is used, interference can never occur. It is, *in principle*, possible to know which path $(t$-t or r-$r)$ the pair took to contribute to a coin-

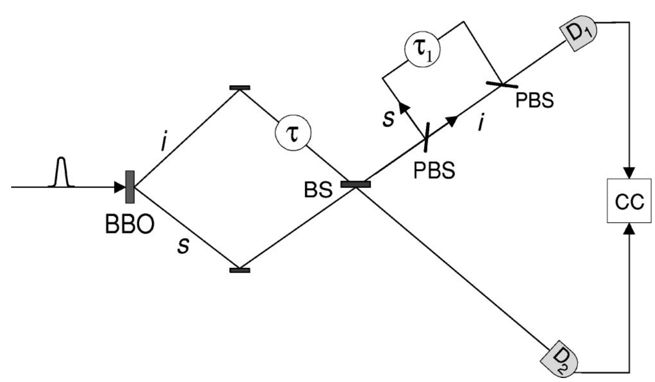

FIG. 1. Schematic of the experiment with a single pump pulse. The idler (i) is delayed by τ before reaching the BS and the signal (s) is delayed by τ_1 after leaving the BS; however, only in one arm of the interferometer.

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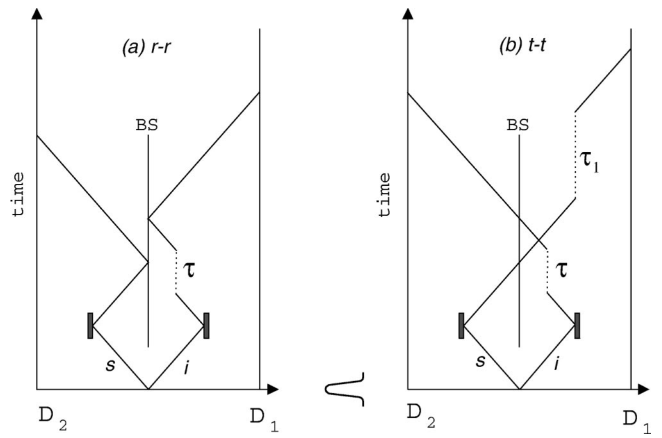

FIG. 2. Feynman diagrams for the single pulse case. Two amplitudes are distinguishable since the pump pulse acts as a clock.

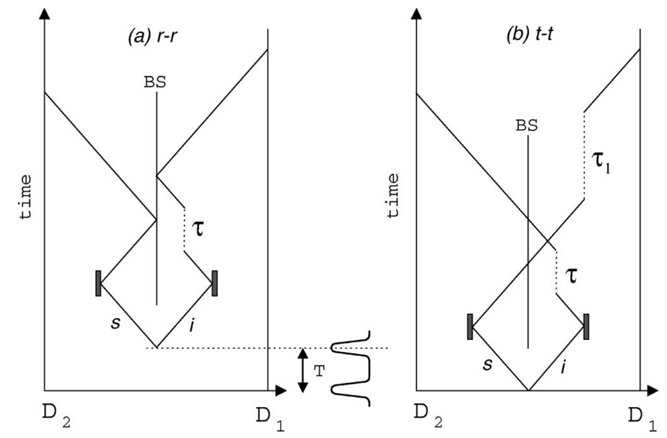

FIG. 3. Feynman diagrams for the two-pulse case. r-r (first pulse) and t-t (second pulse) are indistinguishable with respect to coincidence detections.

cidence count. See the Feynman diagrams in Fig. 2. One could, *in principle*, distinguish t-t and r-r amplitudes by measuring the time difference between the pulse pump and the coincidence detection since the pump pulse would act as a clock that fixes the origin of the biphoton. In other words, the Feynman alternatives that originate from a single pulse are distinguishable. It is clear that no interference will be observed in this case.

In a formal quantum-mechanical representation, the coincidence counting rate (fourth-order interference) is given by integrals over the firing times of the two detectors, T_1 and T_2, respectively [5],

$$R_c \propto \frac{1}{T}\int_0^T dT_1 dT_2 \langle\Psi|E_1^{(-)}E_2^{(-)}E_2^{(+)}E_1^{(+)}|\Psi\rangle$$
$$= \frac{1}{T}\int_0^T dT_1 dT_2 |\langle 0|E_2^{(+)}E_1^{(+)}|\Psi\rangle|^2, \quad (1)$$

where, for example, $E_1^{(+)}$ is the field operator that contains annihilation operators for a photon arriving at detector D_1. $|\Psi\rangle$ is the two-photon state of SPDC. Then, in the case of a single pump pulse, as shown in Fig. 1, the *biphoton wave packets* are ''superposed'' in the form [4]

$$\langle 0|E_2^{(+)}E_1^{(+)}|\Psi\rangle = -\sin\theta_1 \cos\theta_2 A(t_+ - \tau_1, t_{12} - 2\tau + \tau_1)$$
$$+ \cos\theta_1 \sin\theta_2 A(t_+, -t_{12}), \quad (2)$$

where $t_+ \equiv \frac{1}{2}(t_1 + t_2 - 2\tau)$, $t_{12} \equiv t_1 - t_2 + \tau$, and $t_i = T_i - l_i/c$, $i = 1,2$, with l_i denoting the optical path length from the output face of the BBO crystal to detector D_i. $\sin\theta_i$ and $\cos\theta_i$ are the result of projecting the polarization states of the photons onto the detector analyzers.

In Eq. (2) the first term represents the amplitude (wave packet) where both the signal and the idler are transmitted (t-t) at the beam splitter (BS), and the second term represents the amplitude (wave packet) where both are reflected (r-r) at the beam splitter. To observe interference, the t-t and the r-r biphoton amplitudes must be indistinguishable (or the two wave packets should overlap) for a given detection time pair (t_1, t_2). The indistinguishability of the two Feynman alternatives implies that it is, *in principle*, impossible to tell the biphoton path from the detection times. Formal calculation shows [4] that the two biphoton amplitudes cannot be *indistinguishable* (*or overlapped*) when we choose a delay $\tau, \tau_1 > \sigma_{pulse}$, the pump pulse width, as in our experiment. Thus the interference cannot occur in our experimental setup from a single pulse pump.

Now we might ask ourselves, in the case of $\tau > \sigma_{pulse}$, whether it would be possible to ''recover'' quantum interference. The answer is ''yes.'' This can be accomplished by introducing a second pulse delayed in time T with $T = \tau > \sigma_{pulse}$. This solution may come with a surprising question: Can interference occur between two temporally distinguishable pulses? The answer is also ''yes.'' Figure 3 shows the Feynman diagrams for this two-pulse-pump scheme. It has been shown that there are certain conditions to be satisfied in order to observe interference in this two-pulse-pump case [4],

$$T = \tau, \quad 2\tau = \tau_1. \quad (3)$$

When this condition is satisfied, even though (i) the two pump pulses are well distinguishable in time, and (ii) detection events for the signal or the idler are distinguishable, *the r-r amplitude from the first pulse* and *the t-t amplitude from the second pulse* are indistinguishable with respect to coincidence detections. This is illustrated in Fig. 3. This is a two-photon interference phenomenon between biphoton amplitudes that originates from two temporally well-separated pulses.

Naturally, another question arises. Do we still expect 100% interference visibility in this double-pulse interference scheme? Surprisingly, the answer is ''no.'' The maximum interference visibility that one would expect, in this case, is found to be 50%. Detailed theoretical calculations can be found in Ref. [4]. Here we provide a simple explanation based on the Feynman diagrams; see Fig. 3. The coincidence counting rate is proportional to $|\langle 0|E_2^{(+)}E_1^{(+)}|\Psi\rangle|^2$. We now have four amplitudes that could result in coincidence counts. Therefore,

$$R_c \propto |A_{1tt} + A_{2tt} + A_{1rr} + A_{2rr}|^2, \quad (4)$$

where A_1 and A_2 represent the biphoton amplitudes resulting from the first and the second pump pulses, respectively. Sub-

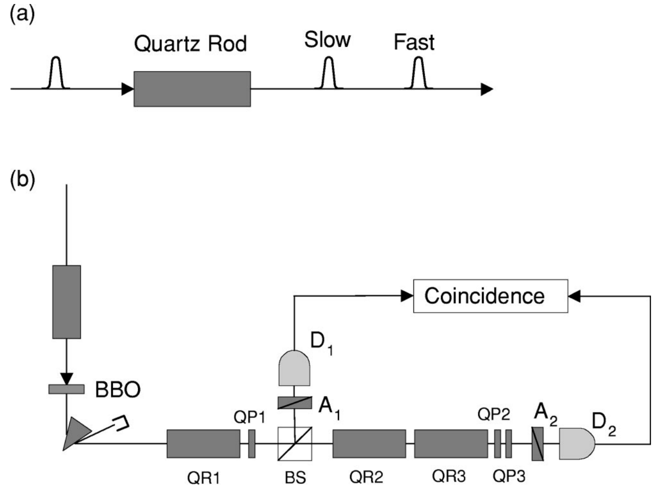

FIG. 4. (a) Scheme to produce a train of two pulses. See text for details. (b) Experimental setup. Each detector package consists of a short focus lens, an interference filter with 10-nm full width at half maximum, and an avalanche photodiode.

scripts tt and rr simply refer to transmitted-transmitted and reflected-reflected. It is clear from Fig. 3 that amplitudes A_{2tt} and A_{1rr} are indistinguishable with respect to coincidence detections. Therefore, the cross terms lead to nonvanishing interference terms. Other terms, e.g., A_{2rr} and A_{1tt}, are distinguishable: hence the cross terms become zero. $|A_{1rr}|^2 = 1$, and similarly for other terms. This leads to

$$R_c \propto 4 + A_{2tt}A_{1rr}^* + A_{1rr}A_{2tt}^*, \tag{5}$$

which shows 50% visibility in the maximum if A_{2tt} and A_{1rr} completely overlap. This deserves further comment. It is usually understood that quantum phenomena show 100% maximum visibility, while classical correlation of fields show 50% maximum visibility in the fourth-order interference experiments [6]. In our case, however, maximum visibility is 50%, although interference is purely quantum mechanical in nature: it is due to quantum entanglement. It is important to understand that the 50% visibility limitation is purely the result of theory. Experimental imperfections are not considered at all at this point. If we consider multiple pulses ($N>2$) delayed in time T with respect to one another, and include more biphoton amplitudes, the maximum visibility can reach 100% [4].

In our experiment, two temporally separated pump pulses were obtained by transmitting a single pump pulse through a quartz rod with the optic axis normal to the pump beam and rotated by 45° with respect to the pump polarization. See Fig. 4(a). Since the e ray and o ray inside the quartz propagate with different group velocities, the incident single pulse starts to separate into two pulses. The length of the quartz rod controls the delay between the two output pulses: one polarized in the fast axis direction and the other in the slow axis direction of the quartz rod. We can further vary this delay by placing quartz plates after the quartz rod to either make the delay bigger (optic axis parallel to that of the quartz rod) or smaller (optic axis perpendicular to that of the quartz rod). The repetition rate of the original pump pulse was about 90 MHz: thus the distance between adjacent pulses was about 11 nsec. The single pump pulse had about 140-fsec width and a central wavelength of 400 nm. The delay (T) between the two pulses was varied from 160 μm~280 μm (or 533–933 fsec), and a coincidence time window of 3 nsec was used. The use of the 3-nsec coincidence window has no effect on the visibility of the interference fringe, in principle. 3 nsec were chosen simply to cut off unwanted accidental events between a double pulse and the adjacent double pulse that is 11 nsec apart (keep in mind that we have a train of ''double-pulses''). Therefore we can safely say that the two pulses are temporally well separated, and we only accept biphoton amplitudes originating from two neighboring pump pulses with delay T.

In the experiment, we made use of type-II degenerate collinear SPDC ($\lambda_s = \lambda_i = 2\lambda_p$, where s, i, and p stand for signal, idler, and pump, respectively). The schematic of the experiment is shown in Fig. 4(b). In this scheme, an orthogonal polarized signal-idler photon pair (one with horizontal polarization, and the other with vertical polarization) propagates in the same direction as the pump. The thickness of the BBO crystal used in the experiment was 100 μm and the filter bandwidth was chosen to be 10 nm ($l_{coh} \simeq \lambda^2/\Delta\lambda \simeq 64\,\mu$m). Notice that the two pulses did not exist in the BBO crystal at the same time at any moment. The interferometer consists of many quartz rods and quartz plates. If the quartz rods (plates) are placed with the optic axis either parallel or perpendicular to that of the BBO crystal, they introduce delays between the signal-idler photon pair. The first delay (τ: QR1 and QP1) is chosen to be 197 μm (or 657 fsec) and the second delay (τ_1: QR2, QR3, QP2, and QP3) is chosen to be 2×197 μm. Therefore, we have satisfied one of the two conditions for observing two-photon interference from two separate pulses, $\tau_1 = 2\tau$.

To demonstrate the two-photon interference effects, we first show the polarization interference. The analyzer A_2 is fixed at 45° and A_1 is rotated while recording the coincidence and single counts. The single counting rate of the detector D_1 is found to be almost constant, while the coincidence counts show $\sin^2(\theta_1 - \theta_2)$ or $\sin^2(\theta_1 + \theta_2)$ modulation, depending on the phases introduced when changing the interpulse delay T [3,7,8]. We recorded the visibility of this polarization interference while varying the delay T between the two pulses. This is shown in Fig. 5. It is clearly shown that when the delay T is equal to the interferometer delay τ, the maximum visibility, which in this case is 33%, is observed.

We also observed the dependence of the coincidence counting rate on the phase shift between the two pump pulses: the space-time interference [8]. This was done by orienting the two polarizers (A_1 and A_2) at 45° and by placing two additional quartz plates after the quartz rod in Fig. 4(a). By tilting the quartz plates, we introduced an additional phase delay between the pump pulses. From Eqs. (2) and (5), we expect to observe

$$R_c \propto 4 - 2\,\eta(T)\cos(\Omega_p \phi_p), \tag{6}$$

where Ω_p is the pump frequency, ϕ_p is the pump phase delay, and $\eta(T)$ has a value of $0\sim 1$ and reflects the fact that the visibility of the interference fringe depends on the value of the interpulse delay T. For the case of maximum visibility, $\eta(\tau)=1$. The data shown in Fig. 6 demonstrate the de-

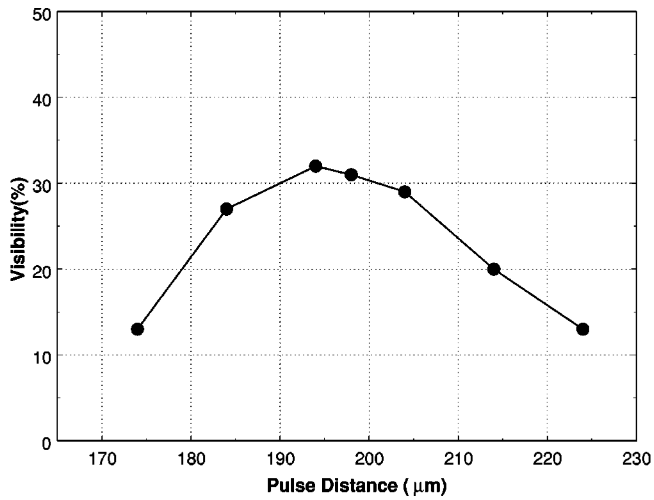

FIG. 5. Visibility change of the polarization interference while the delay between two pulses is varied. When $T=\tau$, maximum visibility was observed.

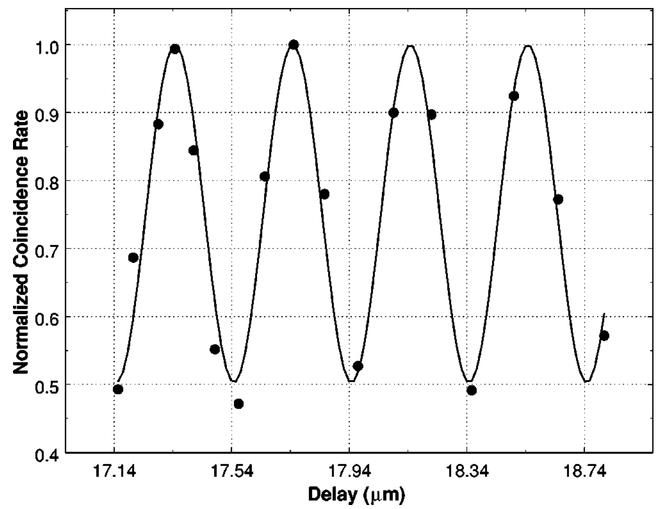

FIG. 6. Space-time interference showing the dependence on pump phase. The modulation period is 400 nm, as expected from Eq. (6).

pendence on pump phase change. The modulation period is 400 nm (pump wavelength), as expected from Eq. (6). Data shown in Figs. 5 and 6 clearly demonstrate two-photon interference effects between the biphoton amplitudes generated from two temporally separated pump pulses.

In conclusion, we have experimentally demonstrated the two-photon interference between biphoton amplitudes arising from two temporally separated pump pulses. It is important to note the following. (i) The pump pulse intensity was low enough so that single counting rates of the detectors were kept much smaller than the pulse repetition rate: the probability of having one SPDC photon pair per pulse in our experiment is negligible. Hence the interference cannot be explained as two SPDC photons from two pump pulses (one SPDC pair from each pulse) interfering at the detectors. The two pump pulses simply provide two biphoton amplitudes that could result in coincidence counts, and interference occurs between these two biphoton amplitudes only when they are indistinguishable. (ii) The BBO crystal in our experiment was only 100 μm thick, so the two pulses did not exist in the BBO crystal at the same time at any moment. (iii) Due to the delays in the interferometer (τ,τ_1), the signal and idler never met at the beam splitter. Therefore, the existence of two-photon interference cannot be viewed as the interference between the signal and the idler photons. These three points again emphasize the fact that it is, indeed, the indistinguishability of the Feynman alternatives for the biphoton amplitudes that is responsible for the quantum interference effects.

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