

Temporal indistinguishability and quantum interference

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A $\chi^{(2)}$ nonlinear optical crystal is pumped by two temporally well-distinguishable femtosecond laser pulses to generate entangled photon pairs in the process of spontaneous parametric down-conversion. We have observed first- and second-order interference between amplitudes generated from the first and the second pump pulse as a function of the time delay between the two pump pulses. The criteria for first- and second-order interference are found to be very different, which reflect the quantum entanglement nature of the state of spontaneous parametric down-conversion.

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Feynman, in discussing the quantum-mechanical superposition, noted that interference occurs when the relevant amplitudes become indistinguishable [1]. In Young's double-slit experiment, there are two equal amplitudes—specific ways for an event to occur, detection of a single photon in this example—of a photon passing through either slit. Interference fringes are observed on the screen if one cannot distinguish the two amplitudes, even in principle. If there is a possibility of knowing which slit the photon passed through, interference disappears (the which-path information is available). Subsequent erasure of the which-path information (quantum erasure) restores the quantum interference even after the quantum being detected [2]. Thus, indistinguishability of the two amplitudes leads to quantum interference. If one considers two-particle (two-photon) interferometry, it is the two-particle amplitudes that are responsible for quantum interference. The two-particle amplitude is a specific path which leads to detection of an entangled particle pair and is identified with joint detection rates (coincidence counts) of the two detectors. See, for example, Ref. [3].

Interference effects observed in experiments in which the sources of the interfering amplitudes are two spatially distinguishable regions have attracted a lot of attention [4]. Although how one generates the interfering amplitudes from two spatially distinguishable regions varies from one experimental situation to another, they basically share the same feature: A cw uv laser beam is split into two beams and each beam is used to pump a region of a $\chi^{(2)}$ nonlinear crystal to generate entangled photon pairs by the process of spontaneous parametric down-conversion (SPDC) [5]. To successfully observe interference effects, the following conditions have to be satisfied: (i) the two pumping laser beams must originate from the same laser source to maintain coherence, (ii) the two SPDC generating crystals must not be separated more than the coherence length of the pump laser beam.

Imposing these two conditions guarantees that interfering amplitudes from two spatially distinguishable regions remain coherent. Once these conditions are satisfied, by spatially and temporally overlapping the signal and the idler modes, one can observe quantum interference either in the single counting rates of the detector or in coincidences.

Quantum interference resulting from two temporally distinguishable pump pulses started to attract attention only recently [6,7]. In these experiments, interfering amplitudes are born at different times from the same $\chi^{(2)}$ nonlinear crystal pumped by two temporally well-separated laser pulses. No active delay lines are introduced either in the signal or in the idler modes to overlap the two pulses. First-order interference has been observed in the angular distribution of the detector plane [6] and second-order interference has also been observed in a postponed compensation-type anticorrelation experiment [7] where the visibility is limited by the theoretical maximum value of 50%. These experiments differ from Ref. [8], in which actual delays equal to the delay between the two pump pulses are introduced in the signal and the idler modes.

In this paper, we report a quantum interference experiment in which the relevant amplitudes are associated with two temporally well-separated femtosecond laser pulses. By varying the phase delay between the two pump laser pulses, both first- (one-photon) and second-order (two-photon) interference are observed in the same setup and the conditions for observing interference are shown to be different. Contrary to Ref. [7], the visibility for second-order interference is not limited to 50%. It is important to note the differences between our experiment and the one in Ref. [8]. In Ref. [8], two-photon entangled states resulting from a Franson interferometer [9] are used. The second pump pulse (delayed exactly equal to the Franson interferometer delay) was necessary, otherwise long-path and short-path amplitudes from the Franson interferometer would become distinguishable. In our experiment, we study how the two temporally distinguishable two-photon amplitudes would be made indistinguishable without introducing actual delay lines equal to the pump pulse delay.

Consider the experimental setup shown in Fig. 1. Two temporally distinguishable pump pulses are obtained by transmitting a femtosecond laser pulse through a quartz rod with the optic axis parallel to the surface and oriented at 45° with respect to the pump polarization. The delay between the two pulses T_p is proportional to the length of the quartz rod.

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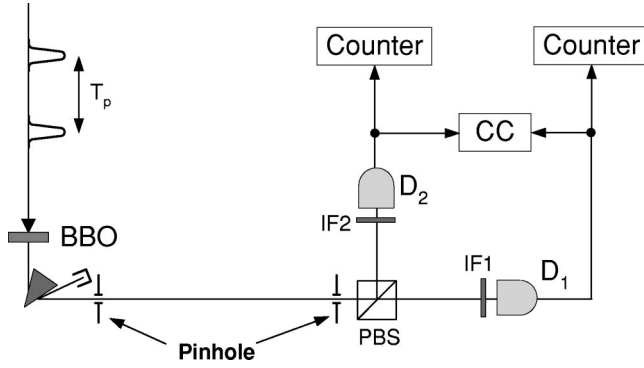


FIG. 1. Experimental setup. A BBO crystal (thickness $L_{\text{BBO}} = 2$ mm) is pumped by two uv pump pulses. PBS is the polarizing beam splitter and CC is the coincidence circuit.

Each pump pulse has a pulse width ~ 84 fsec, and 400 nm central wavelength. The repetition rate of the pulse pair is 82 MHz. T_p can be fine-tuned by inserting and tilting two thin quartz plates in opposite directions without changing the pump beam path, i.e., $T_p + \Delta$. A BBO crystal is then pumped by the two laser pulses. The 800 nm collinear degenerate type-II SPDC is separated from the pump by a fused silica prism and two pinholes. Orthogonally polarized signal and idler photons are then detected by D_2 and D_1 , respectively. Interference filters (IF₁ and IF₂) are placed in front of each detector. The single and coincidence counting rates of the detectors are recorded as a function of the phase delay, Δ , between the two laser pulses. The coincidence time window is 3 nsec. Single detector counting rates (< 1 kHz) are kept much lower than the repetition rate (82 MHz) of the pump pulse pair. We choose $T_p \gg 80$ fsec in the experiment.

The relevant amplitudes A_1 and A_2 , which are associated with the first and the second pump laser pulse, respectively, are naturally “distinguishable” since the two pump laser pulses are distinguishable in time. How can one make these two amplitudes “indistinguishable” in time (or how can one erase the which-path information)? To answer this question, we need to study how the related amplitudes behave as a function of the pump pulse duration and the filter bandwidth in detail.

Let us start from the Hamiltonian of the SPDC [10,11],

$$\mathcal{H} = \epsilon_0 \int d^3\vec{r} \chi^{(2)} E_p(z, t) E_o^{(-)} E_e^{(-)}, \quad (1)$$

where $E_p(z, t)$ is the electric field for the pump pulse, and $E_o^{(-)}$ ($E_e^{(-)}$) is the quantized electric field for the o (e) polarized photon inside the $\chi^{(2)}$ nonlinear crystal (BBO). The pump field can be written as

$$E_p(z, t) = \mathcal{E}_p \int d\omega_p e^{-4 \ln 2 [(\omega_p - \Omega_p)^2 / \sigma_p^2]} e^{i[k_p(\omega_p)z - \omega_p t]}, \quad (2)$$

where \mathcal{E}_p is the amplitude of the pump pulse, Ω_p is the central frequency of the pump pulse, and σ_p is the full width

at half maximum (FWHM) bandwidth of the pump pulse. The state of SPDC is then calculated from first-order perturbation theory,

$$|\psi\rangle = |0\rangle - \frac{i}{\hbar} \int_{-\infty}^{\infty} dt \mathcal{H} |0\rangle. \quad (3)$$

The state vector $|\psi\rangle$ obtained in Eq. (3) is used to calculate the probability of getting a coincidence count [12],

$$R_c \propto \int dt_1 \int dt_2 |\langle 0 | E_2^{(+)} E_1^{(+)} | \psi \rangle|^2. \quad (4)$$

The field at D_1 can be written as

$$E_1^{(+)} = \int d\omega' e^{-4 \ln 2 [(\omega' - \Omega_1)^2 / \sigma_1^2]} e^{-i\omega' t_1} a_o(\omega'), \quad (5)$$

where Ω_1 is the central frequency and σ_1 is the FWHM bandwidth of the filter IF₁. $t_1^o = t_1 - l^o/c$, l^o is the optical path length experienced by the o -polarized photon from the output face of the crystal to D_1 and $a_o(\omega')$ is the destruction operator of the o -polarized photon of frequency ω' . $E_2^{(+)}$ is defined similarly.

We now define the two-photon amplitude (or biphoton) as

$$A(t_+, t_-) = \langle 0 | E_2^{(+)} E_1^{(+)} | \psi \rangle, \quad (6)$$

where $t_+ = (t_1^o + t_2^e)/2$ and $t_- = t_1^o - t_2^e$.

Therefore, the two-photon amplitude originated from each pump pulse has the form

$$\begin{aligned} A(t_+, t_-) &= e^{-i\Omega_p t_+} \int_{-\infty}^{\infty} d\nu_p \int_{-\infty}^{\infty} d\nu_- \int_0^{L_{\text{BBO}}} dz \\ &\times e^{-\nu_p^2 / \delta^2} e^{-2 \ln 2 (\nu_-^2 / \sigma^2)} \\ &\times e^{-i[\nu_p D_+ + (\nu_- / 2) D_-] z} e^{-i\nu_p t_+} e^{-i(\nu_- / 2) t_-} \\ &\equiv e^{-i\Omega_p t_+} \Pi(t_+, t_-), \end{aligned} \quad (7)$$

where we have assumed degenerate SPDC ($\Omega_1 = \Omega_2$), the same filter bandwidth ($\sigma_1 = \sigma_2 \equiv \sigma$), $1/\delta^2 \equiv (2 \ln 2) / \sigma^2 + (4 \ln 2) / \sigma_p^2$, $D_+ \equiv \frac{1}{2} \{ [1/u_o(\Omega_o)] + [1/u_e(\Omega_e)] \} - [1/u_p(\Omega_p)]$, and $D_- \equiv [1/u_o(\Omega_o)] - [1/u_e(\Omega_e)]$. $u_o(\Omega_o)$, for example, is the group velocity of the o -polarized photon of frequency Ω_o inside the BBO. Subscripts o , e , and p , refer to the o -polarized photon, the e -polarized photon, and the pump, respectively. ν_p is the detuning from the pump central frequency Ω_p . ν_o and ν_e are defined similarly and $\nu_- \equiv \nu_o - \nu_e$. Note that, contrary to the cw case [10], Π is a function of both t_+ and t_- .

Having learned the behavior of the biphoton $\Pi(t_+, t_-)$, see Figs. 2, 3(a), and 3(b), we now introduce a second pump pulse delayed by T_p from the first one. The situation is well represented in Fig. 3(c). There are two biphotons each associated with the first and the second pump pulse. They are clearly distinguishable in time when very broadband filters are used. However, if narrowband filters are used instead, each biphoton spreads in both the t_+ and t_- directions. This results in an overlap of two biphotons and indistinguishability increases, see Fig. 3(d). The increased indistinguishability between the two biphotons leads to quantum interference.

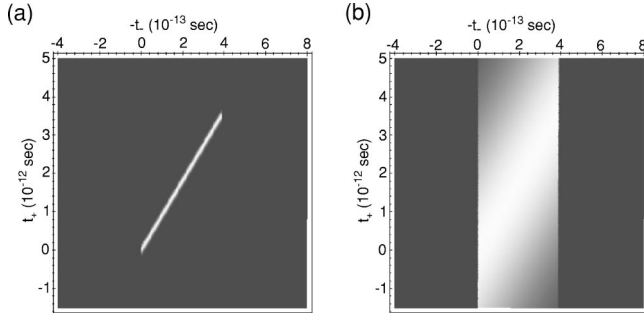


FIG. 2. Calculated two-photon amplitudes as a function of pump bandwidth. Behavior of $\Pi(t_+, t_-)$ is shown in a density plot. (a) Pump pulse duration=80 fsec. In t_- direction, the biphoton starts at 0 and ends at $DL_{\text{BBO}}=387$ fsec as in the case of a cw pump. (b) Pump pulse duration=3 psec. If the pump has infinitely narrow bandwidth, Π function is essentially independent of t_+ .

Formally, the coincidence rate can be written as

$$R_c \propto \int dt_+ \int dt_- |A(t_+, t_-) + A(t_+ + T_p, t_-)|^2 \propto 1 + V \cos(\Omega_p T_p), \quad (8)$$

where V is the visibility resulting from an overlap between the two biphotons. From Eq. (8), we expect that the coincidence counting rate will be modulated in the pump wavelength as T_p is varied.

The experimental data are presented in Fig. 4. In Fig. 4(a), a high visibility interference is observed. As T_p is increased further, visibility of the interference pattern is reduced, see Figs. 4(b) and 4(c). This can be easily understood if we recall

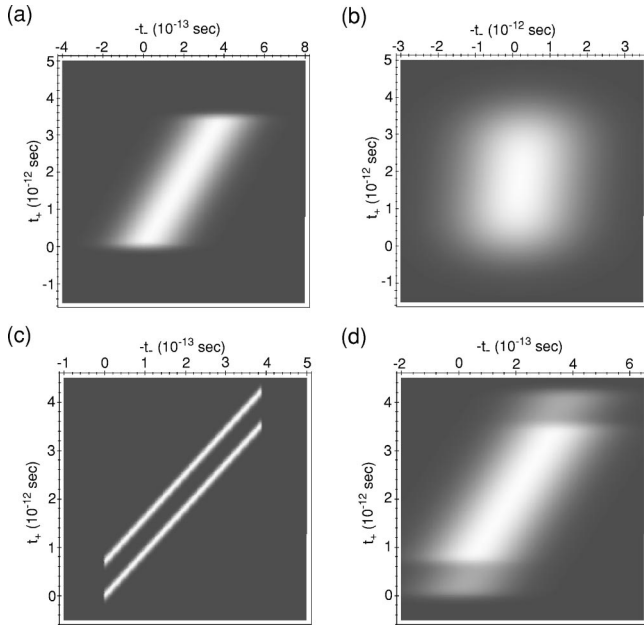


FIG. 3. Calculated two-photon amplitudes as a function of filter bandwidth. Pump pulse duration is 80 fsec. (a) Bandwidth of the filters is set to 10 nm. (b) Filter bandwidths are 1 nm. (c) In the case of two pump pulses. (d) Use of narrowband filters results in overlap between the two biphotons.

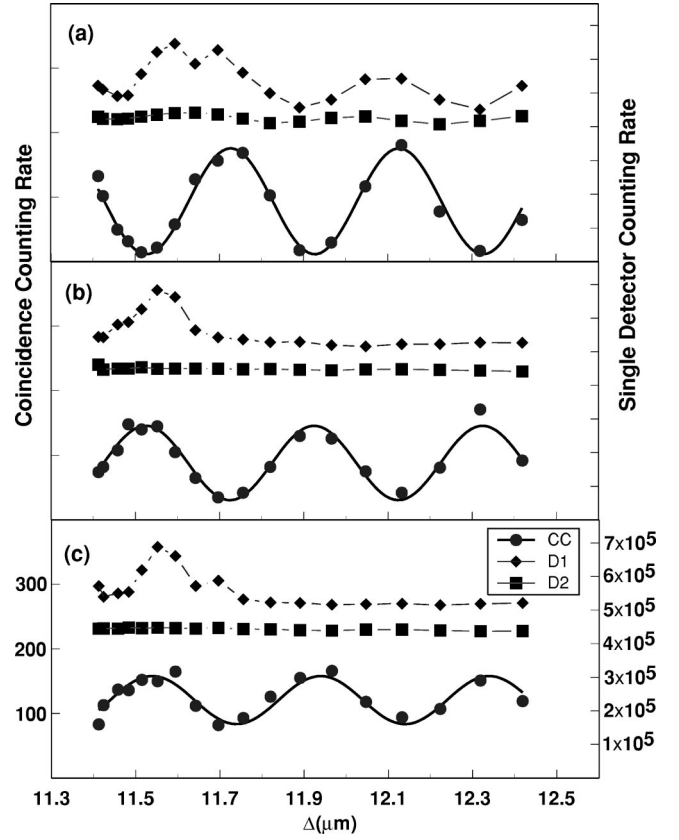


FIG. 4. Experimental data. Bandwidth of both interference filters is 1 nm. For all three plots, the vertical scales and the data accumulation times (10 min) are the same. (a) $T_p=236$ fsec. High visibility interference ($V=87\%$) is observed in coincidence counts. Note also that there is interference in single detector counting rates. (b) $T_p=420$ fsec. $V=65\%$. (c) $T_p=701$ fsec. $V=31\%$. Solid lines in coincidence counting rates are cosine fitting with visibility V as a fitting parameter.

Fig. 3(d). As T_p is increased, the second biphoton moves away from the first one in the t_+ direction. This makes the two biphotons more distinguishable (less overlap) in (t_+, t_-) space, hence we obtain lower visibility. The observed modulation period agrees very well with the theory. A peak in the D_1 counting rate is due to the pump noise.

So far, it is shown that second-order interference is predicted using the biphoton picture of SPDC and the experimental results agree well with the theory. We now turn our attention to first-order interference. Notice that there is modulation in the single counting rates of D_1 and D_2 in Fig. 4(a), which shows a coexistence of first- and second-order interference under certain experimental conditions. Since we are dealing with first-order interference, one-photon amplitudes should be calculated to correctly account for the presence of interference. The one-photon state in the entangled two-photon state can be calculated by taking a partial trace of the two-photon state. For example, the state of the signal photon is $\hat{\rho}_s = \text{tr}_i \hat{\rho}$, where $\hat{\rho} = |\psi\rangle\langle\psi|$, and the subscripts s and i refer to signal and idler, respectively.

When the partial trace is done [6], we find that the conditions for observing interference in the signal beam are

$$\frac{L_{\text{BBO}} \times (u_p^{-1} - u_i^{-1})}{T_p} \gg 1, \quad (9a)$$

$$\Delta \omega_s \ll \frac{\pi}{T_p}, \quad (9b)$$

where u_i (u_p) is the group velocity of the idler (pump) photon inside the BBO crystal. Note in Eq. (9a) that the condition for the signal photon interference depends on the group velocities of the idler and the pump photon inside the BBO crystal. In the classical point of view, the only condition for either signal or idler photon interference is Eq. (9b); the bandwidth of the filters should be narrower than the pump spectrum modulation. [Equation (9b) is satisfied at all times since we choose $\pi/\Delta\omega > 2000$ fsec.] Quantum mechanically, however, the condition for signal photon interference depends on the parameters of the idler photon, too. The physical principle behind this special feature is that the signal and the idler photons are entangled. Although one measures the signal or the idler alone, the signature of entanglement is still there; one cannot simply ignore it.

In Figs. 4(b) and 4(c), first-order interference disappears since the condition discussed in Eq. (9a) is not satisfied anymore. This means that the two one-photon amplitudes from

the two pump pulses are now completely distinguishable. However, second-order interference is still present in coincidences; two-photon amplitudes are still partially indistinguishable. Therefore, we can have a situation in which the two biphoton amplitudes remain indistinguishable, however indistinguishability of the two one-photon amplitudes varies from 0 to 1.

In conclusion, we have studied first-order and second-order interference under the experimental situation in which interference is not expected by the classical theory. (i) The experimental data and theoretical description clearly demonstrate that first-order and second-order interference are of different origin, namely, indistinguishability of one-photon and two-photon amplitudes, respectively. (ii) The signature of entanglement is still present even though one studies a subsystem only. This is important since the nonlocal aspect of the entangled two-photon state is still observed, although only a subsystem is measured.

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