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Quantum-eraser experiment with frequency-entangled photon pairs

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We report a quantum-eraser experiment with frequency-entangled photon pairs generated by nondegenerate parametric down conversion. The relationship between which-path information and two-photon fringe visibility has been investigated by means of photon polarizations in a Hong-Ou-Mandel interferometer. Although photons are not of the same frequency and are not superposed at the beam splitter, the results of the experiment show the revival of the fringe pattern by removing the path information in the interferometer by means of polarizations in front of the detectors.

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One of the characteristic features in quantum physics is the complementarity principle, which excludes the possibility of situations, which exhibits both the wave and particle aspects of a quantum object simultaneously [1]. The wavelike behavior is manifested in the interference fringe, while the which-path information is understood to be a particle property of the light. As stated by Feynman, in discussing Young's double-slit experiment, the interference only appears in those cases in which it is impossible to determine which path the photons traversed to reach the screen. However, if we were to succeed in measuring the path of each photon, then the interference pattern would be destroyed [2].

A useful tool to study the complementarity of wavelike and particlelike behaviors of photons is a quantum-eraser experiment. Since the first proposal was made by Scully and Drühl [3], quantum-eraser experiments have been discussed extensively in connection with the complementarity between the which-path information and the fringe visibility [4–7]. In most optical interferometric studies, it shows that the appearance of interference results from the *intrinsic indistinguishability* of the path of the photons (thus, lacking in which-path information which leads to the interference) [8]. Since the degree of interference is described by the term *fringe visibility*, it vanishes for the distinguishable photon paths in an interferometer. Recently, some efforts have been focused on to give a quantitative expression for the indistinguishability of the interferometer [6,7].

Several interference experiments based on the concept of the quantum eraser have been carried out with entangled photon pairs produced by the spontaneous parametric down-conversion (SPDC) process [9–15]. The SPDC process has been the simplest way for making pairs of photons in entangled quantum states. In addition, entangled photon pairs can be generated with various degrees of freedom which are correlated in time, momentum, frequency, and polarization. With the help of the photon pairs, various experiments have been performed to test the fundamental issues in quantum mechanics such as the Einstein-Podolsky-Rosen (EPR) correlation [16], Bell type inequalities [17], and more recently in quantum information [18].

To date, all the experiments about the quantum-eraser effect have been done with the photons of the same wavelengths produced by the degenerate SPDC process. In this paper, we present the experiment with photons of different wavelengths, i.e., frequency-entangled photon pairs from the nondegenerate type-I SPDC process. Two spectral filters are used for selection of the two different frequencies in a Hong-Ou-Mandel type interferometer [19]. The center wavelengths of photon pairs are widely separated, so that the two frequency bands of the entangled pair do not overlap. The complementarity relation between the path-information and the two-photon interference fringe is investigated by means of distinguishability of photon polarizations. The quantum-eraser effect is finally examined by removing the polarization information in the paths.

Let us consider two pairs of photons, in which each pair has two photons with different frequency modes ω_1 and ω_2 in a two-photon interferometer as in Fig.1(a). A source S emits two photons in a frequency-entangled state such that if one photon is known to be in a frequency ω_1 then the other one is determined with frequency ω_2, or vice versa, by the phase-matching condition. The two emitted photons travel along two distant and balanced interferometers, independently. In the quantum theory, the initial state is represented by

$$|\Psi\rangle_{\omega_1,\omega_2}=\frac{1}{\sqrt{2}}[|\omega_1\rangle_U|\omega_2\rangle_L+|\omega_2\rangle_U|\omega_1\rangle_L], \tag{1}$$

where subscripts U and L represent upper and lower paths of the two-photon interferometer respectively. The state $|\Psi\rangle$ describes a coherent superposition of two distinct pairs of correlated frequencies. In one pair (the black pair), a photon ω_1 in the upper path is reflected from a mirror to a beam splitter (BS), from which it proceeds either to detector D_1 or to detector D_1', while the conjugate photon ω_2 in the lower path is reflected from the mirror to the other BS, from which it proceeds to detector D_2 or D_2'. In the other pair (the white pair), ω_2 in the upper path proceeds to D_2 or D_2', while ω_1 in the lower path proceeds to D_1 or D_1'.

If both BS's have the reflectivity and the transmissivity of 50:50 then the quantum-mechanical probability amplitude after the BS's which is associated with coincidence detection by the detector pairs (D_1,D_2) or (D_1',D_2') is described as

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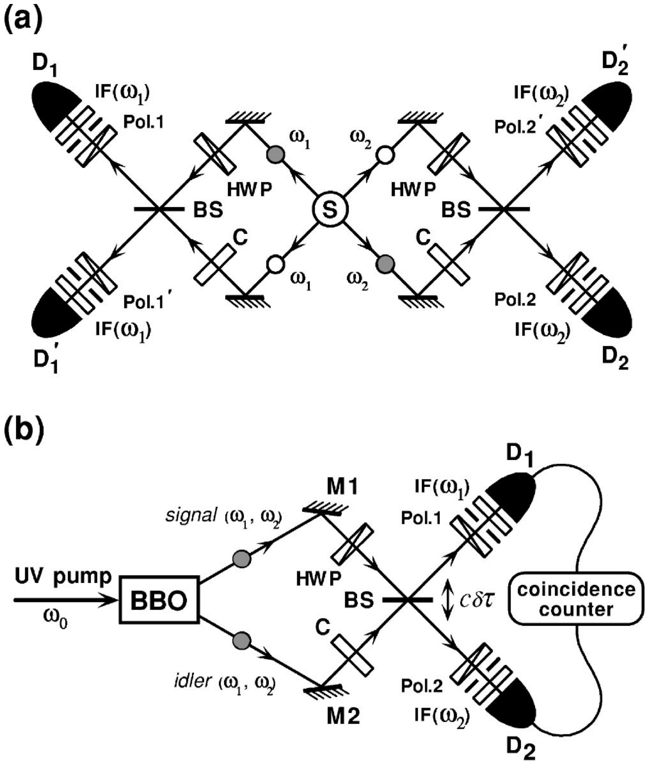

FIG. 1. (a) Two-photon interferometer employing frequency entangled photon pairs. In this illustration, the simultaneous photons with different frequencies (ω_1,ω_2) do not arrive at the same beam splitter (BS), and they do not overlap. (b) Schematic diagram of the experimental setup. A UV pump (cw He-Cd laser line of 325 nm) is used to pump the BBO crystal. HWP, half-wave plate; Pol.1, Pol.2, polarizers; IF, interference filters with center wavelengths 630.1 nm and 671 nm, respectively; D_1,D_2, single photon counting module; BS, nonpolarizing beam splitter; M_1,M_2, mirrors; $c\delta\tau$ introduces a phase shift between two paths.

$$|\psi\rangle_{D_1,D_2}=\frac{1}{2\sqrt{2}}(|\omega_1^L\rangle_{D_1}|\omega_2^U\rangle_{D_2}-e^{i\xi}|\omega_1^U\rangle_{D_1}|\omega_2^L\rangle_{D_2}), \tag{2}$$

where the subscripts denote the propagation modes of photons to detectors D_1 and D_2 after the BS's, and the superscripts U, L describe the upper and lower paths, respectively. The phase factor $e^{i\xi}$ arises from the phase shift between two states by a fine displacement of the BS's or mirrors. In this case, the interference effect in coincidence detection with two detectors D_1 and D_2 is expected because the detectors cannot distinguish between the photon pairs ω_1^L,ω_2^U and ω_1^U,ω_2^L.

To explore the relation between the which-path information and the two-photon interference with the frequency-entangled pairs, we now consider the case in which a pair of half-wave plates (HWP) at an angle $\phi/2$ to the horizon are inserted into the upper paths of the two-photon interferometers. The compensators (C) are put into the lower paths to make up for the optical path lengths of the half wave plate. Then, the polarization directions of the photons ω_1 and ω_2 in the upper paths are rotated by ϕ, making the two Feynman paths partially distinguishable. In the case $\phi/2=45°$, the polarization directions of the two photons with different frequencies reaching the BS are orthogonal. Therefore, the two paths are now completely distinguishable and the amplitudes are squared before being summed. In this special case where $\phi=90°$, the two photons after the BS are in a distinguishable state of photon polarization, in principle:

$$|\psi\rangle_{D_1,D_2}^{\phi=90°}=\frac{1}{2\sqrt{2}}[|\omega_1(H)\rangle_{D_1}|\omega_2(V)\rangle_{D_2} - e^{i\xi}|\omega_1(V)\rangle_{D_1}|\omega_2(H)\rangle_{D_2}], \tag{3}$$

where H and V represent the horizontal and vertical polarizations of photons respectively.

A schematic diagram of the experimental arrangement is shown in Fig. 1(b), which is a well-known Hong-Ou-Mandel interferometer with different frequencies of photons emitted by the SPDC process [19]. This setup is topologically equivalent to the interferometer with two spatial modes shown in Fig. 1(a). For the entangled photon source, a cw He-Cd laser line of 325 nm (Liconix 3207N) is used to pump a $5\times5\times7$ mm^3 β-BaB$_2$O$_4$ (BBO) nonlinear crystal oriented at 36.6° to the optic axis. In this type-I process, two photons with horizontal polarization are emitted simultaneously with different frequencies ω_1 and ω_2 (or separate spatial modes) for the vertically polarized pump beam. If one photon is emitted in a signal path with frequency ω_1 then the other one is emitted in a idler path with frequency ω_2, or vice versa. The two photons are incident on the nonpolarizing beam splitter (BS) which has reflectivity and transmissivity of 50:50. A HWP is inserted in the signal path in order to change the direction of polarization, and a glass plate with the same thickness is put in the other paths to compensate the optical path length of the HWP. Two avalanche photodiode detectors D_1,D_2 (EG&G model SPCM-AQ-141) are located 1 m from the BS, which is about 2 m away from the BBO crystal. Lenses with 10 cm focal length are located in front of small apertures (not shown in the schematic diagram), which are used to focus the beam onto the active area (180 μm diameter) of those detectors. The output pulses of the photon detectors are then sent to single-channel counters and to a coincidence counter with a 6.38 ns time resolution (LeCroy Model 1434A).

In this experiment, we use frequency-entangled photon pairs in an arrangement similar to that suggested by Horne *et al.* [20]. However, frequency (or mode) selection is implemented by the two interference filters in front of the two detectors. The bandwidth of the two filters is centered on different wavelengths of 630.5 and 671 nm, and each filter has a bandwidth of 10 nm. Therefore, the two frequency bands do not overlap in spectrum, so that each detector responds to different frequency components ω_1 and ω_2. The BS can be displaced from its symmetric position ($\delta\tau=0$) by small distances $\pm c\,\delta\tau$ for the differences between the arrival times of the two photons.

Figure 2 shows the measured coincidence counts, with two detectors D_1 and D_2, as a function of the beam splitter position when HWP angles are oriented at 0°, 22.5°, and

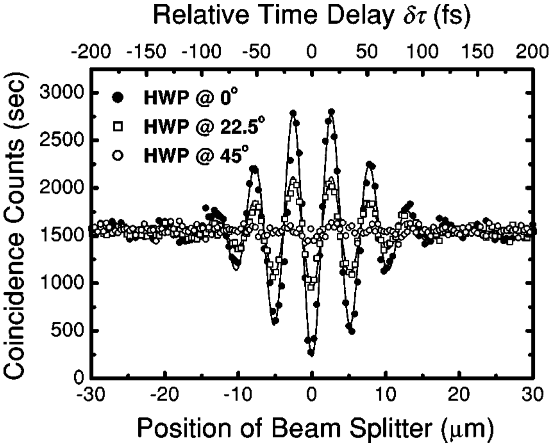

FIG. 2. Coincidence counts as a function of the beam splitter position, (i) with the angle of HWP at 0°, coincidence fringe visibility $V=0.81$ (filled circles), (ii) the polarization direction of signal photons rotated 45° by means of the rotation angle of HWP at 22.5°, $V=0.38$ (open squares), and (iii) the polarization direction of signal photons rotated 90° by means of the rotation angle of HWP at 45°, $V=0$ (open circles), respectively. These results show the complementarity between which-path information and the interference by polarization distinguishability and fringe visibility.

45° to the horizontal direction, respectively. In the case of 0° (filled circles), the two photons are in the same horizontal polarization, so that the two detectors cannot distinguish between the photon pairs ω_1^s,ω_2^i and ω_2^s,ω_1^i. The upper horizontal axis corresponds to the relative time delay $\delta\tau$ between signal and idler photons at the beam splitter. Because of the mirror image, the actual time delay doubles the displacement of the BS. The coincidence counts exhibit a modulation of the form $\cos(\omega_1-\omega_2)\delta\tau$, and the beat frequency is of the order of 1.8×10^{14} rad/s. The maximum visibility of the beat fringe is found to be about 0.81.

To make sure that the interference pattern diminishes for the case of some which-path information available, we rotated the polarization direction of the signal photons by ϕ of the HWP in the signal path. Open squares in Fig. 2 show the measured coincidence counts as a function of the BS position when the polarization direction is rotated by 45°. The visibility of the interference pattern is reduced to 0.38. When the polarization direction between signal and idler photons differs by 90°, the interference fringe does not appear at all (open circles). The path information, which determines the path distinguishability in the interferometer, is given by the angle difference between the two polarization directions.

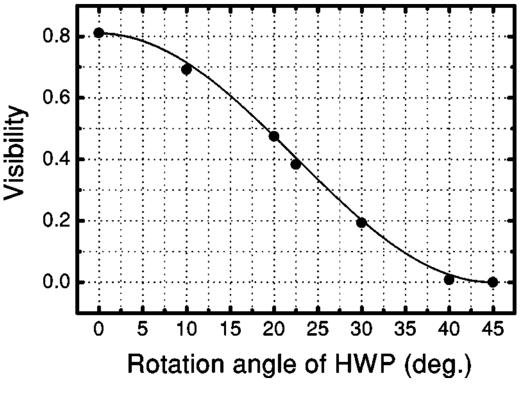

FIG. 3. Two-photon interference visibility as a function of the rotation angle of the HWP.

Figure 3 shows the measured visibility for the different angles of the HWP. The solid line is the curve plotted by $0.81\cos^2\phi$. As we have seen in Eq. (3), with the HWP at 45°, the two paths leading to the coincidence count (reflection-reflection and transmission-transmission) are distinguishable, and they leave each port in the orthogonal polarization states. Therefore, the probability amplitudes are added incoherently, and there is no interference. These results confirm the complementarity relationship between which-path information by polarization directions and the visibility of the interference fringe in the experiment with frequency-entangled photon pairs.

To observe the quantum-eraser effect, we put two polarizers in front of the two detectors to erase the polarization information in the paths. If linear polarizers are set at angles θ_1 and θ_2 to the horizontal, respectively, then the probability for joint detection of the two photons by the two detectors D_1 and D_2 is given as follows:

$$P_{D_1,D_2}=\frac{1}{8}\sin^2(\theta_1+\theta_2). \tag{4}$$

In this case of $\theta_1=\theta_2=\pm45°$, all the path information can be removed for the distinguishable path ($\phi=90°$). The two photons before the detectors are in a *double entangled state* of frequency and polarization. Figure 4(a) shows the mea-

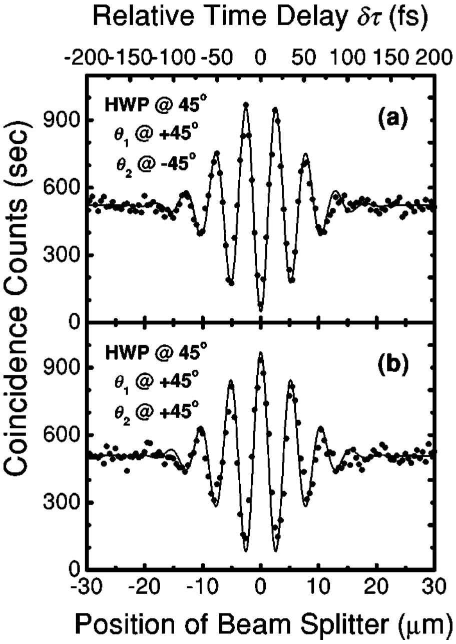

FIG. 4. Coincidence counts as a function of the beam splitter position when the angle of HWP is oriented at 45°, (a) with polarizer angles at $\theta_1=+45°$, $\theta_2=-45°$ ($V=0.86$), and (b) with polarizer angles at $\theta_1=+45°$, $\theta_2=+45°$ ($V=0.84$), respectively. The which-path information is effectively erased by the recombination of polarization components in front of the two detectors.

sured coincidence counts as a function of the BS position when the angle of the HWP is at 45° and the angles of the polarizers are oriented at $\theta_1 = +45°$ and $\theta_2 = -45°$ to the horizontal direction. These results depict the revival of the interference pattern which has been destroyed by the polarization distinguishability introduced by the HWP. The observed interference visibility is about 0.86. Furthermore, when the angles of the two polarizers are at $\theta_1 = +45°$ and $\theta_2 = +45°$, we have another interference fringe as shown in Fig. 4(b). In this case, the coincidence count at zero path-length difference has the maximum value as predicted in Eq. (4). These curves provide the facts that the which-path information is effectively erased by the two polarizers, and that the initial interference pattern is restored for the case of indistinguishable paths, even with nonidentical photons in frequencies. This is interpreted as that the observed effect is caused by an interference of two-photons in a frequency-entangled state via polarization correlation.

In conclusion, the relationship between path information and two-photon interference fringe is examined by means of distinguishability of photon polarizations. The results of the experiment agree well with the prediction of quantum mechanics, the complementarity principle, even with different wavelengths of photons. This scheme can be applied to EPR experiment as well as to other interference experiments such as the Bell-state analysis based on the frequency and the polarization postselection.

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[1] N. Bohr, Naturwissenschaften **16**, 245 (1928).

[2] R. Feynman *et al.*, *The Feynman Lectures on Physics* (Addison, Wesley, Reading, MA, 1965), Vol. III.

[3] M.O. Scully and K. Drühl, Phys. Rev. A **25**, 2208 (1982).

[4] M.O. Scully, B.-G. Englert, and H. Walther, Nature (London) **351**, 111 (1991).

[5] P.G. Kwiat, A.M. Steinberg, and R.Y. Chiao, Phys. Rev. A **49**, 61 (1994).

[6] G. Gjörk and A. Karlsson, Phys. Rev. A **58**, 3477 (1998).

[7] S. Dürr, T. Nonn, and G. Rempe, Phys. Rev. Lett. **81**, 5705 (1998).

[8] L. Mandel, Opt. Lett. **16**, 1882 (1991); X.Y. Zou, L.J. Wang, and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991); G. Di Giuseppe, L. Haiberger, F. De Martini, and A.V. Sergienko, Phys. Rev. A **56**, R21 (1997); D. Branning, W.P. Grice, R. Erdmann, and I.A. Walmsley, Phys. Rev. Lett. **83**, 955 (1999); Y.-H. Kim, M.V. Chekhova, S.P. Kulik, and Y. Shih, Phys. Rev. A **60**, R37 (1999); P.H. Souto Ribeiro, S. Padua, and C.H. Monken, Opt. Commun. **186**, 143 (2000);

[9] P.G. Kwiat, A.M. Steinberg, and R.Y. Chiao, Phys. Rev. A **45**, 7729 (1992).

[10] T.J. Herzog, P.G. Kwiat, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **75**, 3034 (1995).

[11] T.B. Pittman, D.V. Strekalov, A. Migdall, M.H. Rubin, A.V. Sergienko, and Y.H. Shih, Phys. Rev. Lett. **77**, 1917 (1996).

[12] T.G. Noh and C.K. Hong, J. Korean Phys. Soc. **33**, 383 (1998).

[13] Y.H. Kim, R. Yu, S.P. Kulik, Y.H. Shih, and M.O. Scully, Phys. Rev. Lett. **84**, 1 (2000).

[14] Tedros Tsegaye, Gunnar Björk, Mete Atatüre, Alexander V. Sergienko, Bahaa E.A. Saleh, and Malvin C. Teich, Phys. Rev. A **62**, 032106 (2000).

[15] S.P. Walborn, M.O. Terra Cunha, S. Pádua, and C.H. Monken, Phys. Rev. A **65**, 033818 (2002).

[16] Y.H. Shih and C.O. Alley, Phys. Rev. Lett. **61**, 2921 (1988); T.E. Kiess, Y.H. Shih, A.V. Sergienko, and C.O. Alley, *ibid.* **71**, 3893 (1993).

[17] Z.Y. Ou and L. Mandel, Phys. Rev. Lett. **61**, 50 (1988); J.G. Rarity and P.R. Tapster, *ibid.* **64**, 2495 (1990); T.B. Pittman, Y.H. Shih, A.V. Sergienko, and M.H. Rubin, Phys. Rev. A **51**, 3495 (1995).

[18] *The Physics of Quantum Information*, edited by D. Bouwmeester, A. Ekert, and A. Zeilinger (Springer, Berlin, 2001).

[19] Z.Y. Ou and L. Mandel, Phys. Rev. Lett. **61**, 54 (1988); Heonoh Kim, Jeonghoon Ko, and Taesoo Kim, J. Opt. Soc. Am. B **20**, 760 (2003).

[20] M.A. Horne, A. Shimony, and A. Zeilinger, Phys. Rev. Lett. **62**, 2209 (1989).