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Another Quantum Eraser Experiment with Two-photon States of Light

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The quantum eraser experiment was revisited, using entangled photons of visible light in a Hong-Ou-Mandel type interferometer with a magnitude two orders higher than before in count rates. We introduced which-path information by polarization and subsequently erasied this information by means of polarizers in front of detectors. It was found that the visibility of the interference fringe is revived from 0% to 88% as the polarizers are changed from 0° to 45°.

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I. INTRODUCTION

Elementary particles have wave-like and particle-like properties. However the interference pattern and one-path information in an interferometer are impossible to obtain at the same time. If anyone attempts to have which-path information in a interferometer, then he'll fail to find the interference fringe. In other words, the interference fringe will disappear as long as the paths in the interferometer are distinguishable. It is well known as Bohr's complementarity principle [1].

Scully et al. proposed experiments, in which distinguishability can be erased by adequate measurements of the which-path detectors [2]. Interference may be recovered, however, if one somehow manages to erase the distinguishing information. This is the main idea of the quantum eraser experiment [3–8]. In recent years a number of quantum eraser experiments have been performed with pairs of photons generated by the spontaneous parametric down-conversion (SPDC) process [9–13]. SPDC is a three-wave mixing process in which the pump photon of frequency ω_0 is incident in a nonlinear medium and splits into two photons of lower frequency, historically known as signal and idler photon [14]. The two photons usually emerge in different directions simultaneously, but in a highly correlated way, called an entangled quantum state [15–17].

In this paper, we employ the Hong-Ou-Mandel interferometer and the photon pairs produced by SPDC as a interfering system, with count rates of about 6,000 counts/s (70 counts/s). We carried out the same kind of experiment as before, but this time an improved version with count rates two orders of magnitude higher [18]. The which-path information is provided by placing a half-wave plate (HWP) in one path of the interferometer, so that the extent of the path information becomes different according to the rotated direction of the photon polarization in the path. With the angle of a HWP at 45°, the path information is completely available. Polarizers before the two detectors are used to erase the path information. For the polarizers set at the degree of 45°, the path information is erased, which leads to the appearance of the fringe.

II. EXPERIMENTS

The experimental setup is shown in Fig. 1. A laser line of 325 nm from an He-Cd laser (He-Cd 3207N, Liconix) is used as the pump beam for the interaction with a BBO (beta-barium borate; $\beta - BaB_2O_4$) crystal. Two signal and idler beams that generate photons with a wavelength of 650 nm are generated, and emerge from the crystal at the same angles relative to the pump beam. The crystal is cut with the direction of the optic axis at 36.6° with respect to the end faces. For a type-I phase matching condition, the polarizations of the two down-converted beams are the same and parallel to the optical table surface for the perpendicular pump beam.

The two down-converted beams are directed by mirrors M_1 and M_2 to a beam splitter (BS), where they

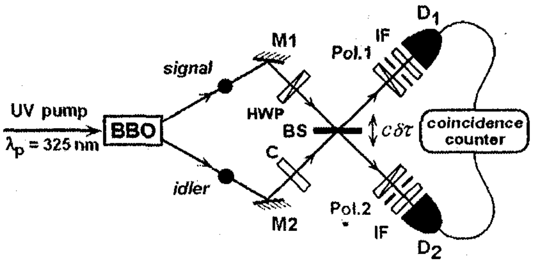


FIG. 1. Schematic diagram of quantum eraser experiment; Hong-Ou-Mandel's interferometer with a half-wave plate and polarizers.

come together. The two outgoing beams from the BS are fed to two Si-APDs (silicon avalanche photodiodes ; EG&G model SPCM-AQ-141-FC) D_1 and D_2, with two pinholes and two nearly identical interference filters which are centered at 650 nm with a 10 nm bandwidth. The photoelectric signals from D_1 and D_2 are transmitted into CAMAC system with a resolving time of 6.38 ns for coincidence measurements.

III. THEORY

Consider two photons incident on a 50/50 beam splitter from different sides. Since each photon has the same possibility of being transmitted or reflected, there would be four possible outcomes as shown in Fig. 2, in which each has the same probability of occurence. The two outcomes (a) and (b) will result in the coincidence count of the photons occuring at each of the output ports at the same time, whereas (c) and (d) wouldn't. If only (c) and (d) cases happen in this situation, it cannot be interpreted classically.

Let's consider that the photon annihilation operators of the input and output modes of the BS are related by the operator equations [19],

$$\hat{a}_3 = \frac{i}{\sqrt{2}}\hat{a}_1 + \frac{1}{\sqrt{2}}\hat{a}_2,$$
$$\hat{a}_4 = \frac{1}{\sqrt{2}}\hat{a}_1 + \frac{i}{\sqrt{2}}\hat{a}_2. \quad (1)$$

These annihilation operators and their conjugate creation operators satisfy the commutation relations $[\hat{a}_i, \hat{a}_j] = 0$ and $[\hat{a}_i, \hat{a}_j^\dagger] = \delta_{ij}$ for $(i,j) = (1,2)$. If the coincidence detection is carried out with two detectors at two output ports of the BS, the expectation of the coincidence measurement for the general input photons states, $|n_1, n_2\rangle$, is obtained as

$$\langle \hat{N}_c \rangle = \langle n_1, n_2| : \hat{n}_3 \hat{n}_4 : |n_1, n_2\rangle$$
$$= \frac{1}{4}[n_1(n_1-1) + n_2(n_2-1)]. \quad (2)$$

For the special case where $n_1 = n_2 = 1$, which corresponds to a coincident input of simultaneous photons generated in parametric down-conversion, the coincidence count rate goes to zero. This means that the coincident photons always exit the BS together along the same path of the interferometer. If the two photons are described in quantum theory by the two-photon Fock state $|1_{\text{signal}}, 1_{\text{idler}}\rangle$, then the wave function on the output states of the beam splitter can be shown to be [20]

$$|\Phi\rangle_{c\delta\tau=0} = \frac{i}{\sqrt{2}}\left[|2_1 0_2\rangle + |0_1 2_2\rangle\right], \quad (3)$$

where the subscript of $|\Phi\rangle$ means zero path-length difference, and the subscripts 1, 2 indicate the propagation modes to the two detectors.

To introduce the polarization property of the two photons, a half-wave plate (HWP) at an angle to the horizon is inserted into one input arm of the interferometer. The degree of photon polarization is twice the angle of the HWP. If one sets a HWP at 45°, this makes the photon vertically polarized. Let's consider the following number-state basis wave function after the beam splitter with polarization information [3,6]:

$$|\Psi\rangle_{c\delta\tau=0} = \frac{1}{\sqrt{2}}\left[\left|1_1^H 1_2^{H+\phi}\right\rangle - \left|1_1^{H+\phi} 1_2^H\right\rangle\right], \quad (4)$$

where the number indicates the photodetector, H is horizontally polarized, and $1_{1,2}^{H+\phi}$ means that the photon is polarized at an angle ϕ to the horizon. To give a better understanding of polarizations, the probability of a coincidence count is explained by the vector operators

$$\hat{a}_{\text{m}}^\dagger = \hat{a}_{\text{m,H}}^\dagger \cdot \epsilon_{\text{m,H}} + \hat{a}_{\text{m,V}}^\dagger \cdot \epsilon_{\text{m,V}},$$
$$\hat{a}_{\text{m}} = \hat{a}_{\text{m,H}} \cdot \epsilon_{\text{m,H}} + \hat{a}_{\text{m,V}} \cdot \epsilon_{\text{m,V}}, \quad (5)$$

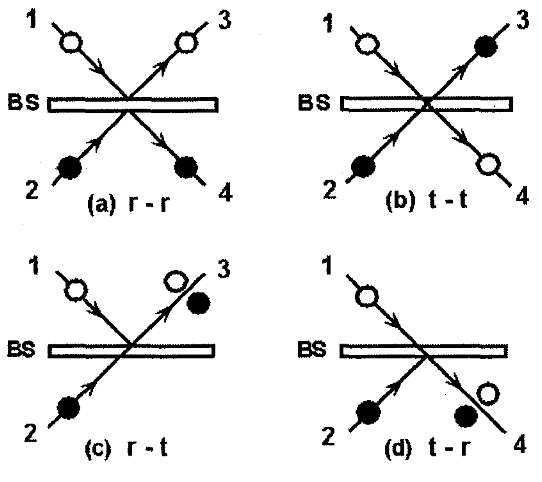


FIG. 2. Four possible outcomes for two photons incident on a beam splitter from different sides.

where m indicates the detectors and $\epsilon_{\mathrm{m,H}}$ and $\epsilon_{\mathrm{m,V}}$ are horizontal and vertical polarization vectors, respectively. Then the probability of the coincidence count $\hat{P}_c$ is obtained as

$$\begin{aligned}\hat{P}_c &\equiv \sum_{\lambda_1,\lambda_2=H,V} a^\dagger_{1,\lambda_1} a^\dagger_{2,\lambda_2} a_{2,\lambda_2} a_{1,\lambda_1} \\ &= \sum_{\lambda_1,\lambda_2=H,V} a^\dagger_{1,\lambda_1} a_{1,\lambda_1} a^\dagger_{2,\lambda_2} a_{2,\lambda_2} \\ &= (\hat{\mathrm{a}}_1^\dagger \cdot \hat{\mathrm{a}}_1)(\hat{\mathrm{a}}_2^\dagger \cdot \hat{\mathrm{a}}_2) \\ &= (\hat{a}^\dagger_{1,H}\hat{a}_{1,H} + \hat{a}^\dagger_{1,V}\hat{a}_{1,V})(\hat{a}^\dagger_{2,H}\hat{a}_{2,H} + \hat{a}^\dagger_{2,V}\hat{a}_{2,V}). \quad (6)\end{aligned}$$

Using the expansion $|1_{\mathrm{m}}^{H+\phi}\rangle = |1_{\mathrm{m}}^{H}\rangle \cos\phi + |1_{\mathrm{m}}^{V}\rangle \sin\phi$, the probability of coincidence counting in two detectors is given by

$$P_{\mathrm{coin}}(0) \approx \langle\Psi|\hat{P}_c|\Psi\rangle_{c\delta\tau=0} = \frac{1}{2}\sin^2\phi, \quad (7)$$

for the zero path-length difference. When the path-length difference is longer than the coherence length of the down-converted photon, the coincidence rate is then

$$\begin{aligned}P_{\mathrm{coin}}(c\delta\tau \gg \tau_c) &\approx \frac{1}{4}\left\langle 1_1^H 1_2^{H+\phi}\left|\hat{P}_c\right| 1_1^H 1_2^{H+\phi}\right\rangle \\ &+ \frac{i^4}{4}\left\langle 1_1^{H+\phi} 1_2^H\left|\hat{P}_c\right| 1_1^{H+\phi} 1_2^H\right\rangle \\ &= \frac{1}{2}. \quad (8)\end{aligned}$$

The visibility of interference pattern in coincidence counts is defined as

$$V = \frac{P_c(c\delta\tau \gg \tau_c) - P_c(c\delta\tau = 0)}{P_c(c\delta\tau \gg \tau_c)}. \quad (9)$$

Therefore the visibility has the form of $\cos^2\phi$, according to the doubled angle of the HWP. For the HWP placed at angle of 45° in one arm of the interferometer, and no polarizers in front of detectors, the wave function projected for the HWP from the entangled state in Eq (4) is then

$$|\Psi\rangle_{c\delta\tau=0} = \frac{1}{\sqrt{2}}\sin\phi\left[\left|1_1^H 1_2^V\right\rangle - \left|1_1^V 1_2^H\right\rangle\right] \quad (10)$$

If the linear polarizers P_1 and P_2 are placed in front of detectors D_1 and D_2, and rotated as θ_1 and θ_2 with respect to the horizon, respectively, then the state vectors appropriate for the two polarizers are

$$\begin{aligned}|\theta_1\rangle &= \left(\left|1_1^H\right\rangle\cos\theta_1 + \left|1_1^V\right\rangle\sin\theta_1\right), \\ |\theta_2\rangle &= \left(\left|1_2^V\right\rangle\sin\theta_2 - \left|1_2^H\right\rangle\cos\theta_2\right). \quad (11)\end{aligned}$$

Consequently, the state after the polarizer P_1 is as follows

$$\langle\theta_1|\Psi\rangle_{c\delta\tau=0} = \frac{1}{\sqrt{2}}\sin\phi\left[\left|1_2^V\right\rangle\cos\theta_1 - \left|1_2^H\right\rangle\sin\theta_1\right]. \quad (12)$$

After having passed through the two polarizers P_1 and P_2, the expectation value is given by

$$\langle\theta_2\theta_1|\Psi\rangle_{c\delta\tau=0} = \frac{1}{\sqrt{2}}\sin\phi\sin(\theta_2+\theta_1), \quad (13)$$

which is the probability amplitude of the state for coincidence counting. Therefore the probability of coincident detection is

$$P_{\mathrm{coin}}(0) \approx \left|\langle\theta_1\theta_2|\Psi\rangle_{c\delta\tau=0}\right|^2 = \frac{1}{2}\sin^2\phi\sin^2(\theta_2+\theta_1). \quad (14)$$

Hence the interference is dependent on the relative angle of the polarizers [see Fig. 5].

IV. RESULTS AND DISCUSSION

To make sure the interference effect in a HOM interferometer is actually occuring, the coincidence count was measured as a function of the position of the beam splitter (BS). Fig. 3 shows the typical interference pattern as the BS is scanned through the symmetric position, where a dip is observed [20]. Next, a HWP is inserted into one input path of the interferometer to obtain which-path information, as depicted in Fig. 1. Then, the polarization of the photon is rotated by ϕ to make the two paths partially distinguishable [see Fig. 4].

In the case of the HWP at 22.5° the visibility is decreased to one half the case of $\phi = 0°$ [closed circles in Fig. 4(a)]. The interference fringe disappears as shown by the open circles in Fig. 4(a). for the HWP at 45°. This is because all paths are distinguishable due to the fact that the polarization states of the signal and idler photons are orthogonal. The visibility

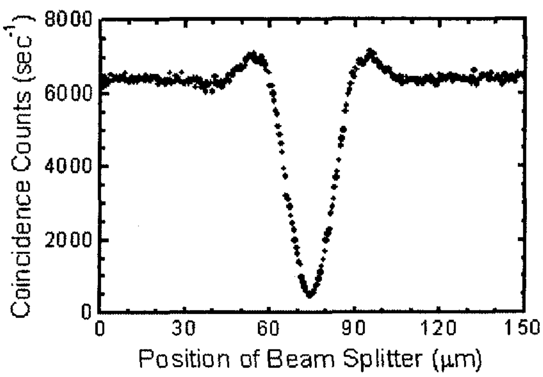
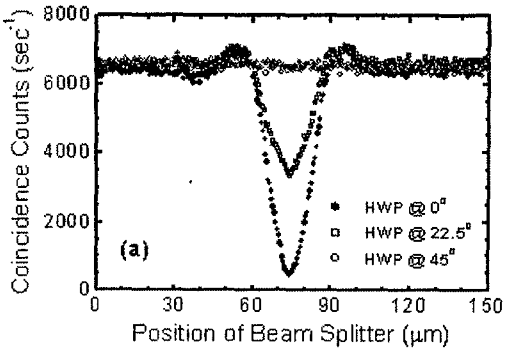
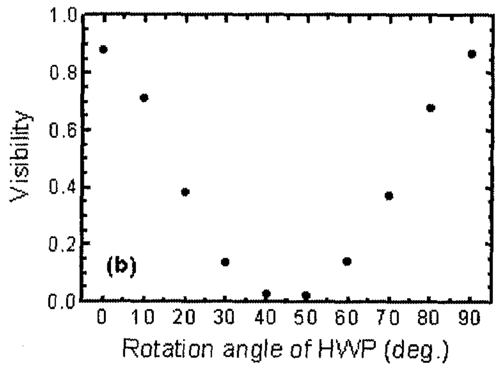


FIG. 3. The measured number of coincidence counts as a function of the beam splitter position.

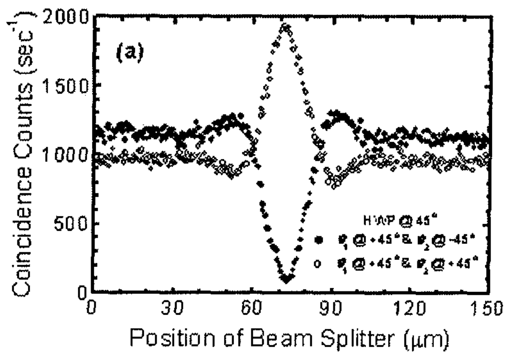


(a)

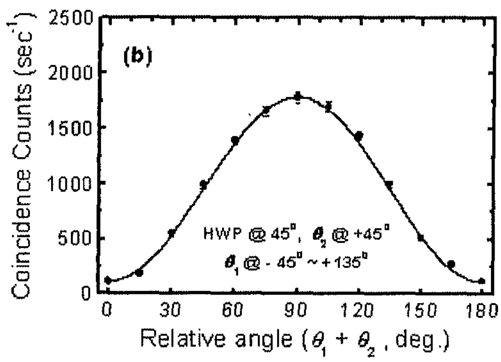


(b)

FIG. 4. (a) The coincidence counts for three angles of the half-wave plate. (b) Visibility as a function of the angle of the half-wave plate.



(a)



(b)

FIG. 5. The quantum eraser effect in HOM interference experiments. (a) The coincidence counts as a function of beam splitter position, when P_1 and P_2 is placed at +45° and ±45°. (b) Coincidence counts as a function of the relative angle between the two polarizers at zero path length difference position.

is measured as a function of the HWP angle. Fig. 4(b) shows the results of the which-path information and the visibility which are mutually exclusive for the angle of the HWP from 0° through 90°.

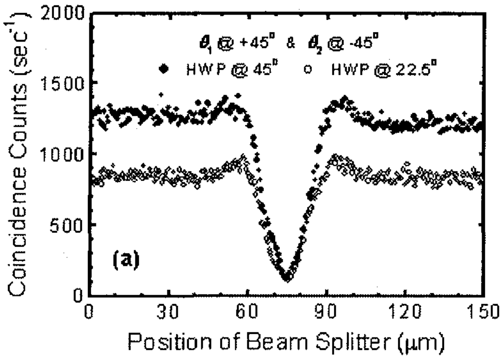
With the angle of the HWP at 45°, the photons arriving at the detectors have the path information. If we put the polarizers in front of the detectors the path information is erased by the polarizers, especially when $\theta_1 = +45°, \theta_2 = -45°$, in which case the information is expected to be erased completely. Fig. 5(a) reinforces the interference fringe for this case [closed circles]. In the case where the polarizers are set at $\theta_1 = +45°, \theta_2 = +45°$, the path information is still unavailable at the detectors. The open circles in Fig. 5(a) reveal an interference pattern, as a peak at the symmetric position of the BS, instead of a dip.

Fig. 5(b) shows the coincidence counts at the dip position for different angles of θ_1, while θ_2 is fixed at +45°. The amplitudes for the transmission-transmission and reflection-reflection have a phase difference of π at the zero path-length difference position. *Since the phase difference of π is compensated* by the two polarizers placed in front of the two detectors, the amplitudes are added up in a constructive way to have a peak instead of a dip. Fig. 6 shows the results where the interference fringe is revived when the path information is not available in the detecter's point of view and the change of coincidence counts at the dip position for the angle of the HWP.

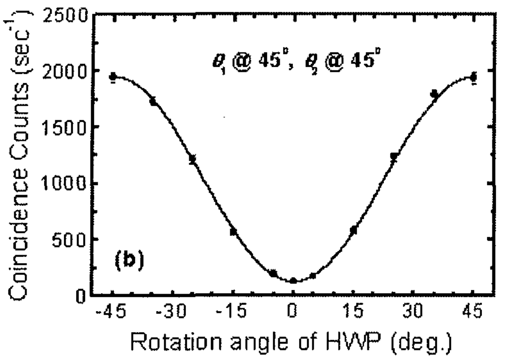
V. CONCLUSION

We have performed quantum eraser experiments with photon pairs in order to demonstrate the mutual exclusivity between observing interference and which-path information, as demanded by Bohr's complementarity principle.

The photon pairs produced by SPDC are directed to input ports of a beam splitter with $T = R = 50\%$. When the two photons reached the beam splitter at the same time, they always appeared together on either output ports of the beam splitter. This kind of property results in an interference dip in the coincidence counts. However, if the path lengths of the photon pair are longer than the coherence length of one, then no interference but coincidences are observed.



(a)



(b)

FIG. 6. (a) The interference fringes of two different angles of HWP at $\theta_1 = +45°$, and $\theta_1 = -45°$. (b) Coincidence counts at the dip with both polarizers fixed at $+45°$ for the different angle of the HWP from $-45°$ to $+45°$.

We used a half-wave plate to change the polarization direction of one input arm of the interferometer in order to obtain the which-path information. The visibility of the interference is decreased from 88% to 0%, at the angle of a HWP from 0 to 45°. This means that distinguishability of the paths indicates the loss of the interference and the relation between which-path information and visibility is mutually exclusive.

To erase the information we placed the polarizers before the two detectors. The interference fringe is recovered with the angles of polarizers at $\theta_1 = +45°, \theta_2 = +45°$ or $\theta_1 = +45°, \theta_2 = -45°$. The overall coincidence count rate is decreased due to the loss at the polarizers, but the revived interference fringe reaches the same visibility of 88% in the eraser experiment. The experiment is similar to a previous study we conducted in principle [18], but shows more accurate results with much higher counter rates than before.

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