Double-slit quantum eraser

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We report a quantum eraser experiment which actually uses a Young double slit to create interference. The experiment can be considered an optical analogy of an experiment proposed by Scully, Englert, and Walther [Nature (London) **351**, 111 (1991)]. One photon of an entangled pair is incident on a Young double slit of appropriate dimensions to create an interference pattern in a distant detection region. Quarter-wave plates, oriented so that their fast axes are orthogonal, are placed in front of each slit to serve as which-path markers. The quarter-wave plates mark the polarization of the interfering photon and thus destroy the interference pattern. To recover interference, we measure the polarization of the other entangled photon. In addition, we perform the experiment under ''delayed erasure'' circumstances.

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I. INTRODUCTION

Wave-particle duality, a manifestation of the complementarity principle, proposes many questions about the behavior of particles in interferometers. It has long been known that which-path information and visibility of interference fringes are complementary quantities: any distinguishability between the paths of an interferometer destroys the quality (visibility) of the interference fringes. The incompatibility between which-path information and interference effects has been quantified through inequalities by various authors [1–6]. Originally, it was thought that the uncertainty principle was the mechanism responsible for the absence of interference fringes due to a which-path measurement. The first and perhaps most famous example of this idea is the Einstein-Bohr dialogue at the Fifth Solvay Conference in Brussels concerning Einstein's recoiling double-slit gedanken experiment, in which the momentum transfer from incident particles to the double slit is measured to determine the particles' trajectories [7,8]. However, Bohr showed that the uncertainty in the knowledge of the double slit's initial position was of the same order of magnitude as the space between the interference minima and maxima: interference fringes were ''washed out'' due to the uncertainty principle [7].

More recently, Scully and Drühl have shown that, in certain cases, we can attribute this loss of interference not to the uncertainty principle but to quantum entanglement between the interfering particles and the measuring apparatus [9]. For example, disregarding internal degrees of freedom, we can represent the state of particles exiting an interferometer by

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|\psi_1(\mathbf{r})\rangle + |\psi_2(\mathbf{r})\rangle], \tag{1}$$

where $|\psi_1(\mathbf{r})\rangle$ and $|\psi_2(\mathbf{r})\rangle$ represent the possibility for the particles to take path 1 or 2, respectively. The probability distribution for one-particle detection at a point $\mathbf{r}$ is given by $|\langle \mathbf{r}|\Psi\rangle|^2$; the cross terms $\langle\psi_1(\mathbf{r})|\mathbf{r}\rangle\langle\mathbf{r}|\psi_2(\mathbf{r})\rangle$ and $\langle\psi_2(\mathbf{r})|\mathbf{r}\rangle \times\langle\mathbf{r}|\psi_1(\mathbf{r})\rangle$ are responsible for interference. The introduction of an apparatus M capable of marking the path taken by a particle without disturbing $|\psi_1(\mathbf{r})\rangle$ or $|\psi_2(\mathbf{r})\rangle$ can be represented by the expansion of the Hilbert space of the system in the following way:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|\psi_1(\mathbf{r})\rangle|M_1\rangle + |\psi_2(\mathbf{r})\rangle|M_2\rangle], \tag{2}$$

where $|M_j\rangle$ is the state of the which-path marker corresponding to the possibility of passage through the path j. The which-path marker has become entangled with the two possible particle states. A 100% effective which-path marker is prepared such that $|M_1\rangle$ is orthogonal to $|M_2\rangle$. In this case, a measurement of M reduces $|\Psi\rangle$ to the appropriate state for the passage of the particle through path 1 or 2. However, the disappearance of the interference pattern is not dependent on such a measurement. The which-path marker's presence alone is sufficient to make the two terms on the right-hand side of Eq. (2) orthogonal and thus there will be no cross terms in $|\langle \mathbf{r}|\Psi\rangle|^2$. Therefore, it is enough that the which-path information is available to destroy interference. Moreover, provided that $|\psi_1(\mathbf{r})\rangle$ and $|\psi_2(\mathbf{r})\rangle$ are not significantly perturbed by the observer, one can *erase* the which-path information and recover interference by correlating the particle detection with an appropriate measurement on the which-path markers. Such a measurement is known as *quantum erasure*. In addition, if the which-path marker is capable of storing information, the erasure can be performed even after the detection of the particle. The possibility of delayed erasure generated a discussion with respect to its legitimacy, with the argument that it would be possible, in this way, to alter the past [11,12]. This argument is founded on an erroneous interpretation of the formalism of quantum mechanics [13,14]. In recent years, there have been a number of ideas and experiments (performed and proposed) in which which-path information is accessible without causing severe perturbations to the interfering particles [10,9,15–30]. Among the proposals, we distinguish the ones due to Scully and Drühl [9] and to Scully, Englert, and Walther [10] because of their originality and pedagogical content.

Because of their momentum, time, and polarization correlation properties, photon pairs generated by spontaneous parametric down-conversion play an important role in the experimental demonstrations of quantum erasure [17,18,20,21,28,29]. Although the quantum erasure phenomenon is present in all reported experiments, only one [28] can be considered an optical analog of the original proposal of Scully and Drühl [9]. In this paper we report a quantum eraser experiment which actually uses a Young double slit to create interference. The experiment is analyzed in connection with the proposal of Scully, Englert, and Walther (SEW) [10,31]. To the authors' knowledge, this is the first demonstration of a quantum eraser in which interference is obtained from the passage of the particles through a real double slit.

In Sec. II we give a brief summary of the SEW quantum eraser. The theory behind our quantum eraser is presented in Sec. III. The experimental setup and results are presented in Secs. IV and V, respectively.

II. THE SCULLY-ENGLERT-WALTHER QUANTUM ERASER

The experiment reported here is inspired by the proposal of Scully, Englert, and Walther [10], which can be summarized as follows. A beam of Rydberg atoms in an excited state is incident on a double slit small enough to form a Young interference pattern on a distant screen. In front of each slit is placed a which-path marker, which consists of a micromaser cavity of appropriate length such that the emission probability for an atom traversing the cavity is 1. Then the presence of a photon in either cavity marks the passage of an atom through the corresponding slit and thus destroys the interference pattern, because which-path information is now available. The perturbation to the spatial part of the wave function of the atoms due to the cavities is ignorable [10,13,31]. A measurement that projects the state of the cavities onto a symmetric (antisymmetric) combination of $|0\rangle$ (no photon present) and $|1\rangle$ (one photon present) performs the erasure, and an interference pattern is recovered in correlated detection.

III. AN OPTICAL BELL-STATE QUANTUM ERASER

Consider the following experimental setup. A linearly polarized beam of photons is incident on a double slit. If the double slit is of appropriate dimensions, the probability distribution for one-photon detection at a distant screen is given by a Young interference pattern. Suppose that in front of each slit we place a quarter-wave plate, with the fast axis at an angle of 45° (or −45°) with respect to the photon polarization direction. Upon traversing either one of the wave plates, the photon becomes circularly polarized, and acquires a well-defined angular momentum [32]. Supposing that the wave plate is free to rotate, it should acquire an angular momentum opposite to that of the photon, and rotate right or left, depending on the chirality of the photon. If we treat each wave plate as a quantum rotor, we can say that the photon induced a transition with $\Delta l = \pm 1$. Since the wave plates do not significantly modify the propagation of the beam, we have, in principle, a which-path marker with necessary characteristics for a quantum eraser. However, this scheme is far from being practical. As well as the difficulty of setting the wave plates free to rotate, the separation between the energy levels of a rotor with the mass and dimensions of a wave plate is of the order 10^{-40} eV. In addition, decoherence effects may make it impossible to use macroscopic quantum rotors to mark the path of a photon. This idea is similar to the ''haunted measurement'' of Greenberger and Ya'sin [33].

By enlarging the system, however, it is possible to create an adequate which-path detector. Let the beam of photons incident on the double slit be entangled with a second beam freely propagating in another direction, so as to define a Bell state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|x\rangle_s|y\rangle_p + |y\rangle_s|x\rangle_p), \tag{3}$$

where the indices s and p indicate the two beams, and x and y represent orthogonal linear polarizations. If beam s is incident on the double slit (without wave plates), state (3) is transformed to

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\psi_1\rangle + |\psi_2\rangle), \tag{4}$$

where

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}(|x\rangle_{s1}|y\rangle_p + |y\rangle_{s1}|x\rangle_p), \tag{5}$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(|x\rangle_{s2}|y\rangle_p + |y\rangle_{s2}|x\rangle_p). \tag{6}$$

The indices $s1$ and $s2$ refer to beams generated by slit 1 and slit 2, respectively. The probability distribution for one-photon detection on a screen placed in the far-field region of the overlapping beams $s1$,$s2$ will show the usual interference:

$$P_s(\delta) \propto 1 + \cos\delta, \tag{7}$$

where δ is the phase difference between the paths slit 1 $\rightarrow$detector and slit 2$\rightarrow$detector. Introducing the $\lambda/4$ plates one in front of each slit with the fast axes at angles $\theta_1 = 45°$ and $\theta_2 = -45°$ to the x direction, states $|\psi_1\rangle$ and $|\psi_2\rangle$ are transformed to

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}(|L\rangle_{s1}|y\rangle_p + i|R\rangle_{s1}|x\rangle_p), \tag{8}$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(|R\rangle_{s2}|y\rangle_p - i|L\rangle_{s2}|x\rangle_p), \tag{9}$$

where R and L represent right and left circular polarizations. Since $|\psi_1\rangle$ and $|\psi_2\rangle$ have orthogonal polarizations, there is no possibility of interference. In order to recover interfer-

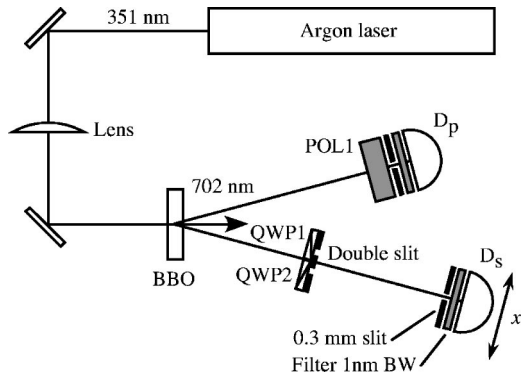

FIG. 1. Experimental setup for the Bell-state quantum eraser. QWP1 and QWP2 are quarter-wave plates aligned in front of the double slit with fast axes perpendicular. POL1 is a linear polarizer.

ence, let us project the state of the system over the symmetric and antisymmetric states of the which-path detector. This is equivalent to transforming $|\psi_1\rangle$ and $|\psi_2\rangle$ in a way that expresses them as symmetric and antisymmetric combinations of polarizations, for example,

$$|x\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle), \tag{10}$$

$$|y\rangle = \frac{1}{\sqrt{2}}(|+\rangle - |-\rangle), \tag{11}$$

$$|R\rangle = \frac{1-i}{2}(|+\rangle + i|-\rangle), \tag{12}$$

$$|L\rangle = \frac{1-i}{2}(i|+\rangle + |-\rangle), \tag{13}$$

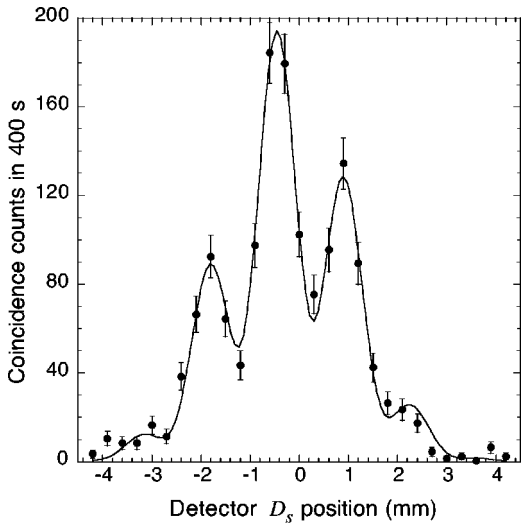

FIG. 2. Coincidence counts vs detector D_s position with QWP1 and QWP2 removed. An interference pattern due to the double slit is observed.

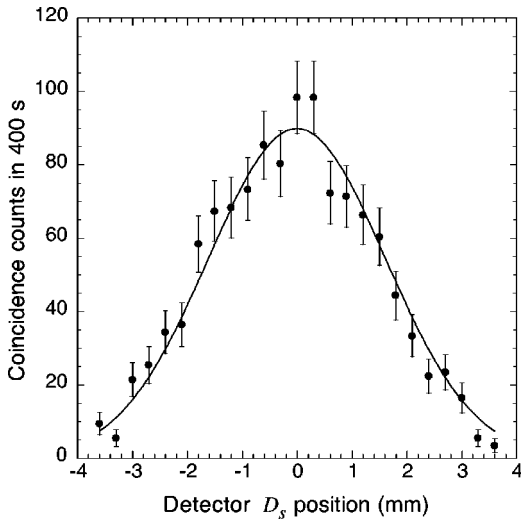

FIG. 3. Coincidence counts when QWP1 and QWP2 are placed in front of the double slit. Interference has been destroyed.

where "+" and "−" represent polarizations +45° and −45° with respect to *x*. Rewriting the complete state $|\Psi\rangle$, we have

$$|\Psi\rangle = \frac{1}{2}[(|+\rangle_{s1} - i|+\rangle_{s2})|+\rangle_p + i(|-\rangle_{s1} + i|-\rangle_{s2})|-\rangle_p]. \tag{14}$$

According to the above expression, we can recover interference projecting the state of photon *p* over $|+\rangle_p$ or $|-\rangle_p$. Experimentally, this can be done by placing a polarizer in the path of beam *p* and orientating it at +45° to select $|+\rangle_p$ or at −45° to select $|-\rangle_p$. The interference pattern is recovered through the coincidence detection of photons *s* and *p*. Notice that the fringes obtained in the two cases are out of phase. They are commonly called *fringes* and *antifringes*.

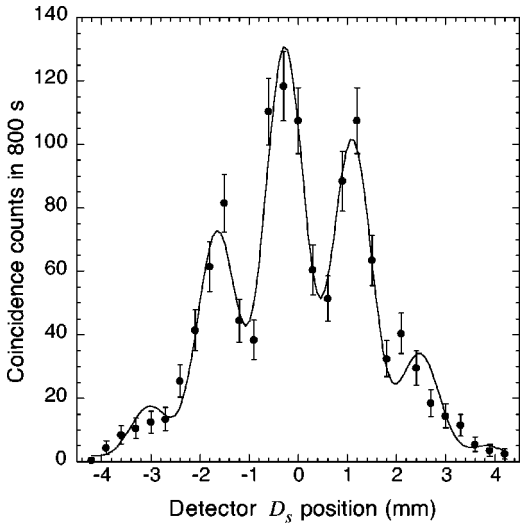

FIG. 4. Coincidence counts when QPW1, QWP2, and POL1 are in place. POL1 was set to θ, the angle of the fast axis of QWP1. Interference has been restored in the *fringe* pattern.

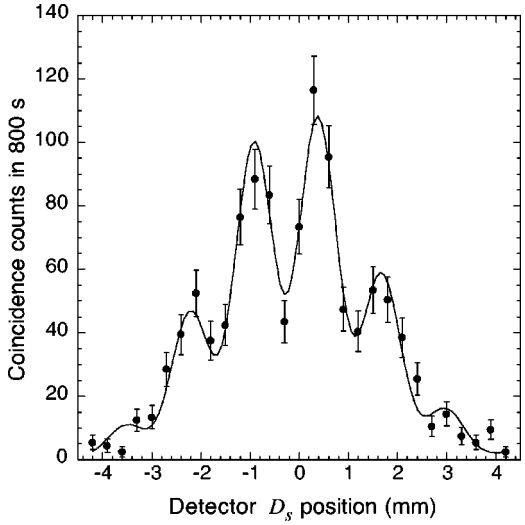

FIG. 5. Coincidence counts when QPW1, QWP2, and POL1 are in place. POL1 was set to $\theta+\pi/2$, the angle of the fast axis of QWP2. Interference has been restored in the *antifringe* pattern.

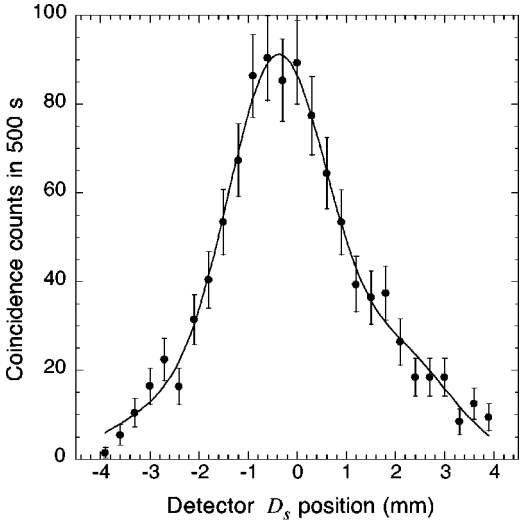

FIG. 7. Coincidence counts in the delayed-erasure setup with QWP1 and QWP2 in place in front of the double slit. No interference is observed.

A. Obtaining which-path information

Which-path information can be obtained by considering the polarization of both photons *s* and *p*. The process of obtaining information can be separated into two schemes: detecting *p* before *s*, or detecting *s* before *p*, which we refer to as *delayed erasure*. This can be done by changing the relative lengths of beams *s* and *p*. We will assume that one photon is detected much earlier than the arrival of the other photon at the measuring devices. Let us consider the first possibility. If photon *p* is detected with polarization *x* (say), then we know that photon *s* has polarization *y* before hitting the $\lambda/4$ plates and the double slit. By looking at Eqs. (4), (8), and (9), it is clear that detection of photon *s* (after the double slit) with polarization *R* is compatible only with the passage of *s* through slit 1 and polarization *L* is compatible only with the passage of *s* through slit 2. This can be verified experimentally. In the usual quantum mechanics language, detection of photon *p* before photon *s* has prepared photon *s* in a certain state.

B. Delayed erasure

The possibility of obtaining which-path information after the detection of photon *s* leads to delayed choice [34]. Delayed choice creates situations in which it is important to have a clear notion of the physical significance of quantum mechanics. A good discussion can be found in Refs. [11–14]. In as much as our quantum eraser does not allow the experimenter to *choose* to observe which-path information or an interference pattern after the detection of photon *s*, it does

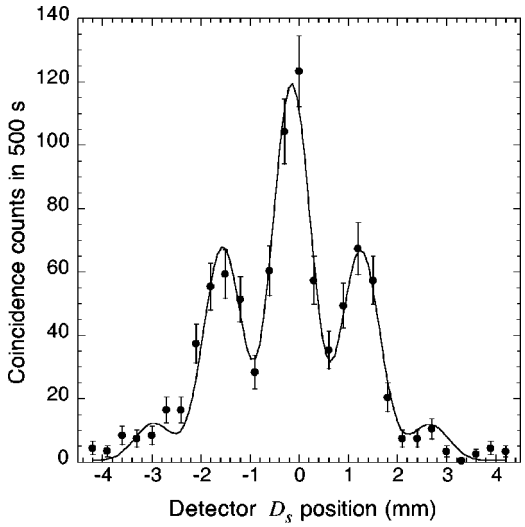

FIG. 6. Coincidence counts in the delayed erasure setup. QWP1, QWP2, and POL1 are absent. A standard Young interference pattern is observed.

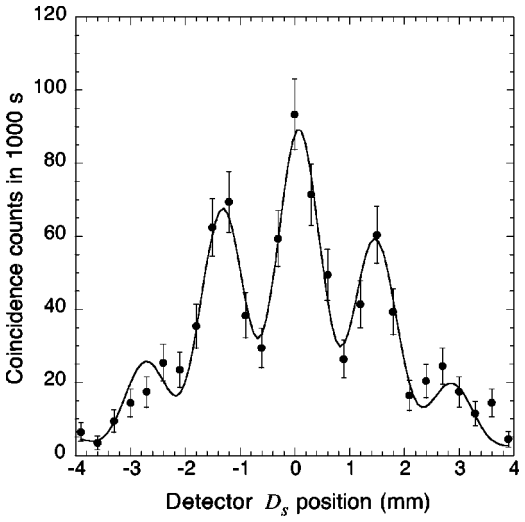

FIG. 8. Coincidence counts in the delayed-erasure setup when QPW1, QWP2, and POL1 are in place. POL1 was set to θ, the angle of the fast axis of QWP1. Interference has been restored in the *fringe* pattern.

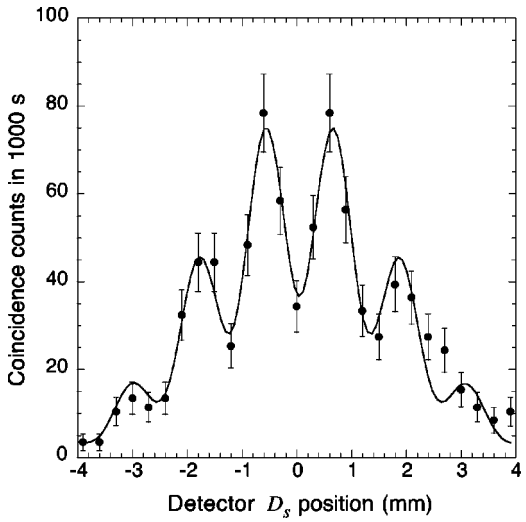

FIG. 9. Coincidence counts in the delayed-erasure setup when QPW1, QWP2, and POL1 are in place. POL1 was set to $\theta + \pi/2$, the angle of the fast axis of QWP2. Interference has been restored in the *antifringe* pattern.

allow for the detection of photon *s* before photon *p*, a situation which we refer to as delayed erasure. The question is, ''Does the order of detection of the two photons affect the experimental results?''

IV. EXPERIMENTAL SETUP AND PROCEDURE

For certain propagation directions, type-II spontaneous parametric down-conversion in a nonlinear crystal creates the state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|o\rangle_s|e\rangle_p + e^{i\phi}|e\rangle_s|o\rangle_p), \tag{15}$$

where *o* and *e* refer to ordinary and extraordinary polarizations. ϕ is a relative phase shift due to the crystal birefringence. If $\phi = 0$ or π we have the Bell states $|\Psi^+\rangle$ and $|\Psi^-\rangle$, respectively.

Using this state in the interferometer described in the previous section, the probability of detecting photons in coincidence is proportional to

$$\frac{1}{2} + \left[\frac{1}{2} - \sin^2(\theta+\alpha)\cos^2\frac{\phi}{2} - \sin^2(\theta-\alpha)\sin^2\frac{\phi}{2}\right]\sin\delta, \tag{16}$$

where δ is defined right after expression (7), θ is the smallest angle between the fast (slow) axis of the quarter-wave plates and the *o* axis, and α is the angle of the polarizer in path *p*, with respect to the *o* axis.

The experimental setup is shown in Fig. 1. An argon laser (351.1 nm at ~200 mW) is used to pump a 1-mm-long BBO (β-BaB_2O_4) crystal, generating 702.2 nm entangled photons by spontaneous parametric down-conversion. The BBO crystal is cut for type-II phase matching. The pump beam is focused onto the crystal plane using a 1 m focal length lens to increase the transverse coherence length at the double slit. The width of the pump beam at the focus is approximately 0.5 mm [35]. The orthogonally polarized entangled photons leave the BBO crystal each at an angle of ~3° with the pump beam. In the path of photon *p* a polarizer cube (POL1) can be inserted in order to perform the quantum erasure. The double slit and quarter-wave plates are placed in path *s*, 42 cm from the BBO crystal. Detectors D_s and D_p are located 125 and 98 cm from the BBO crystal, respectively. QWP1 and QWP2 are quarter-wave plates with fast axes at an angle of 45°. The circular quarter-wave plates were sanded (tangentially) so as to fit together in front of the double slit. The openings of the double slit are 200 μm wide and separated by a distance of 200 μm. The detectors are EG&G SPCM 200 photodetectors, equipped with interference filters (bandwidth 1 nm) and 300 μm$\times$5 mm rectangular collection slits. A stepping motor is used to scan detector D_s.

The delayed erasure setup is similar, with two changes: (i) detector D_p and POL1 were placed at a new distance of 2 m from the BBO crystal and (ii) the collection iris on detector D_p has dimensions 600 μm$\times$5 mm.

V. EXPERIMENTAL RESULTS

Before the quantum eraser experiment was performed, Bell's inequality tests were performed to verify that entangled states were being detected [36]. Figure 2 shows the standard Young interference pattern obtained with the double slit placed in the path of photon *s*, without quarter-wave plates QWP1 and QWP2, and with POL1 absent from detector D_p. Next, the path of photon *s* was marked by placing the quarter-wave plates QWP1 and QWP2 in front of the double slit. Figure 3 shows the absence of interference due to the quarter-wave plates. Nearly all interference present in Fig. 2 was destroyed. The residual interference present is due to a small error in aligning the quarter-wave plates. The which-path information was erased and interference recovered by placing the linear polarizer POL1 in front of detector D_p. To recover interference, the polarization angle of POL1 (α) was set to θ, the angle of the fast axis of quarter-wave plate QWP1. Interference fringes were obtained as shown in Fig. 4. The detection time was doubled in order to compensate for the decrease in coincidence counts due to POL1. In Fig. 5, POL1 was set to $\theta + \pi/2$, the angle of the fast axis of QWP2, which produced a pattern of interference antifringes. The averaged sum of these two interference patterns gives a pattern roughly equal to that of Fig. 3.

The same experimental procedure was used to produce Figs. 6–9 for the delayed-erasure situation. The experimental results are comparable to the case in which photon *p* is detected before photon *s*. We use the term ''delayed choice'' loosely, in that in our experiment there is no ''choice'' available to the observer in the time period after the detection of photons *s* and before the detection of photon *p*. We simply wish to show that the order of detection is not important, in concordance with the literature [13,14].

VI. CONCLUSION

We have presented a quantum eraser that uses a Young double slit to create interference. The quarter-wave plates in

our experiment served as the which-path markers to destroy interference. We recovered interference using the entanglement of photons *s* and *p*. Our quantum eraser is very similar to the that of Scully, Englert, and Walther [10]. We have shown that interference can be destroyed, by marking the path of the interfering photon, and recovered, by making an appropriate measurement on the other entangled photon. We have also investigated this experiment under the conditions of delayed erasure, in which the interfering photon *s* is detected before photon *p*. In as much as our experiment did not allow for the observer to choose the polarization angle in the time period after photon *s* was detected and before detection of *p*, our results show that a *collapse* of the wave function due to detection of photon *s* does not prohibit one from observing the expected results. Our experimental data agree with the proposal of Scully, Englert, and Walther that quantum erasure can be performed after the interfering particle has been detected [10].

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[1] W. K. Wootters and W. H. Zurek, Phys. Rev. D **19**, 473 (1979).
[2] D. M. Greenberger and A. Yasin, Phys. Lett. A **128**, 391 (1988).
[3] L. Mandel, Opt. Lett. **16**, 1882 (1991).
[4] G. Jaeger, A. Shimony, and L. Vaidman, Phys. Rev. A **51**, 54 (1995).
[5] B. G. Englert, Phys. Rev. Lett. **77**, 2154 (1996).
[6] G. Björk and A. Karlsson, Phys. Rev. A **58**, 3477 (1998).
[7] M. Jammer, *The Philosophy of Quantum Mechanics* (Wiley, New York, 1974).
[8] F. Belinfante, *Measurement and Time Reversal in Objective Quantum Theory* (Pergamon, New York, 1975).
[9] M. O. Scully and K. Drühl, Phys. Rev. A **25**, 2208 (1982).
[10] M. O. Scully, B. G. Englert, and H. Walther, Nature (London) **351**, 111 (1991).
[11] U. Mohrhoff, Am. J. Phys. **64**, 1468 (1996).
[12] U. Mohrhoff, Am. J. Phys. **67**, 330 (1999).
[13] M. O. Scully and H. Walther, Found. Phys. **28**, 5229 (1998).
[14] B. G. Englert, M. O. Scully, and H. Walther, Am. J. Phys. **67**, 325 (1999).
[15] M. O. Scully and H. Walther, Phys. Rev. A **39**, 5229 (1989).
[16] M. O. Scully, B. G. Englert, and J. Schwinger, Phys. Rev. A **40**, 1775 (1989).
[17] A. G. Zajonc, L. Wang, X. Ou, and L. Mandel, Nature (London) **353**, 507 (1991).
[18] P. G. Kwiat, A. Steinberg, and R. Chiao, Phys. Rev. A **45**, 7729 (1992).
[19] P. G. Kwiat, A. Steinberg, and R. Chiao, Phys. Rev. A **49**, 61 (1994).
[20] T. J. Herzog, P. G. Kwiat, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **75**, 3034 (1995).
[21] C. H. Monken, D. Branning, and L. Mandel, in *CQO7—Proceedings of the Seventh Rochester Conference in Coherence and Quantum Optics*, edited by L. Mandel and J. Eberly (Plenum, New York, 1996), p. 701.
[22] C. C. Gerry, Phys. Rev. A **53**, 1179 (1996).
[23] Z. Y. Ou, Phys. Lett. A **226**, 323 (1997).
[24] S.-B. Zheng and G.-C. Guo, Physica A **251**, 507 (1998).
[25] G. Hackenbroich, B. Rosenow, and H. A. Weidenmüller, Europhys. Lett. **44**, 693 (1998).
[26] S. Dürr, T. Nonn, and G. Rempe, Nature (London) **395**, 33 (1998).
[27] S. Dürr, T. Nonn, and G. Rempe, Phys. Rev. Lett. **81**, 5705 (1998).
[28] Y. Kim, R. Yu, S. Kulik, Y. Shih, and M. Scully, Phys. Rev. Lett. **84**, 1 (2000).
[29] P. Kwiat, P. Schwindt, and B. G. Englert, in *Workshop on Mysteries, Puzzles, and Paradoxes in Quantum Mechanics*, edited by R. Bonifacio (AIP, Woodbury, NY, 1998).
[30] U. Eichmann *et al.*, Phys. Rev. Lett. **70**, 2359 (1993).
[31] M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, England, 1997).
[32] R. A. Beth, Phys. Rev. **50**, 115 (1936).
[33] D. M. Greenberger and A. Ya'sin, Found. Phys. **19**, 679 (1989).
[34] J. A. Wheeler, in *Mathematical Foundations of Quantum Theory*, edited by A. R. Marlow (Academic, New York, 1978), p. 183.
[35] P. S. Ribeiro, C. Monken, and G. Barbosa, Appl. Opt. **33**, 352 (1994).
[36] P. G. Kwiat *et al.*, Phys. Rev. Lett. **75**, 4337 (1995).