Observation of a "quantum eraser": A revival of coherence in a two-photon interference experiment

Paul G. Kwiat, Aephraim M. Steinberg, and Raymond Y. Chiao
Department of Physics, University of California, Berkeley, California 94720
(Received 23 December 1991)

We have observed an effect known as a quantum eraser, using a setup similar to one previously employed to demonstrate a violation of Bell's inequalities. In this effect, an interfering system is first rendered incoherent by making the alternate Feynman paths which contribute to the overall process distinguishable; with our apparatus this is achieved by placing a half wave plate in one arm of a Hong-Ou-Mandel interferometer so as to rotate the polarization of the light in that arm by 90°. This adds information to the system, in that polarization is a new parameter which serves to label the path of a given photon, even after a recombining beam splitter. The quantum "eraser" removes this information from the state vector, *after* the output port of the interferometer, but in time to cause interference effects to reappear upon coincidence detection. For this purpose, we use two polarizers in front of our detectors. We present experimental results showing how the degree of erasure (which determines the visibility of the interference) depends on the relative orientation of the polarizers, along with theoretical curves. In addition, we show how this procedure may do more than merely erase, in that the act of "pasting together" two previously distinguishable paths can introduce a new relative phase between them.

PACS number(s): 03.65.Bz, 42.50.Wm, 42.50.Dv

I. INTRODUCTION

Interference is arguably the most fundamental effect in quantum mechanics, the Young's two-slit experiment being the canonical manifestation of complementarity. As discussed by Bohr in his classic dialogue with Einstein, if one tries to measure the momentum of the recoiling slits to determine which slit the particle (e.g., photon, electron, atom, etc.) traversed, then one will observe particlelike behavior, and no interference (wavelike behavior) will arise. In a variant of this example, Feynman proposed to "watch" the passage of an electron through a particular slit by placing a light source immediately after the slits and scattering photons off the electron [1]. Even if one does not observe the scattered light, the electron interference will be washed out (whenever the light is scattered sufficiently to carry unambiguous information about which slit was traversed).

This loss of interference is commonly interpreted as arising from uncontrollable, irreversible interactions of the interfering system with the environment, which often takes the form of a macroscopic apparatus [2]. The resulting measurement "reduces" the wave function of the interfering system, including any phase information carried by the particle, thereby eliminating the possibility of interference. In Feynman's example, scattering light off the electron changes its center-of-mass wave function in an uncontrollable manner, removing the phase coherence between the two paths. While it is true that many measurements are of this sort, there are situations where the measurement process need not be so uncontrollable. In these cases it is more helpful to view the loss of coherence as due to an entanglement of the system wave function with that of the measuring apparatus [3]. We will show below how this destroys interference. We can also understand all of these results in terms of Feynman's rules for calculating probabilities: (i) Probability amplitudes of *indistinguishable* paths are summed, then absolute squared, to yield the probability; this leads to interference terms. (ii) Probabilities of *distinguishable* paths are summed, yielding no interference. Thus it is the distinguishability of alternative paths which prevents interference. When information exists about which way *(welcher Weg)* the particle went, the paths are distinguishable, and no interference is possible. Interference may be regained, however, if one somehow manages to "erase" the distinguishing information. This is the central concept of the quantum eraser [4]. A nice review article on this and the related ideas of complementarity recently appeared in Ref. [5].

Scully *et al.* [6] discussed a simple experiment to see this effect, in which an atom is sent through a Stern-Gerlach interferometer [7]. Upon measurement of the atom's passage through one arm of the interferometer, the interference is made to vanish. This is true even if the measuring apparatus does not change the spin state of the atom, or affect the center-of-mass part of its wave function. Unfortunately, detailed calculations of the proposed experiment made clear that it would probably not be feasible in practice, due to the experimental difficulty of controlling the fields to the degree necessary to observe interference, even in the absence of a *welcher Weg* detector [8,9]. Another proposal using a two-slit type interference of neutrons, with micromaser cavities as *welcher Weg* detectors was also deemed very difficult [10]. To date, the most promising of the proposed experiments on particles involve the interference manifested in the quantum beat phenomenon [10,11]. However, in addition to also being rather difficult, though possibly feasible, these experiments suffer the conceptual disadvantage that there are not actually spatially distinct paths as in the double-slit versions. A somewhat different scheme with photons using optical parametric amplifiers as *welcher Weg* detectors was also recently proposed [12]. However, only partial erasure is possible, and even then the practical obstacle of lack of near-unit efficiency photon detectors must be overcome.

As described below, we have performed a comparatively simple experiment involving the interference of photons, which we believe demonstrates all the salient features of the quantum-eraser phenomenon [13]. The *welcher Weg* information is stored in the polarization states of the photons, which are made distinguishable by means of a half wave plate. The erasure is performed by means of polarizers placed before the detectors. In Sec. II we briefly describe our setup and the two-photon light source in our system. The nonclassical interference effect we employ is reviewed in Sec. III, introducing the necessary quantum-field-theory formalism. The loss of this interference is investigated theoretically in Sec. IV, and experimental results are shown. A simple derivation of the quantum-eraser effect is presented in Sec. V, as are experimental results. We show that not only is it possible to recover interference, but also to change the form of the interference pattern. A comparison of our experiment with the various proposals is made in Sec. VI, along with a discussion of its relation to some Bell's inequalities experiments and other two-photon experiments. The main results are summarized in Sec. VII. Throughout we will try to explain the phenomena both at an intuitive level using Feynman's rules, and also at a more formal level, using the established quantum field-theoretic approach to photodetection and correlation.

II. EXPERIMENTAL SETUP

A schematic of our apparatus is shown in Fig. 1. Highly correlated pairs of photons are produced in a nonlinear crystal via the process of spontaneous parametric down-conversion of a uv pump beam, generated by an argon-ion laser. The $\chi^{(2)}$ nonlinear medium is a 10-cm-long potassium dihydrogen phosphate (KDP) crystal, with the direction of the optic axis cut at 53° with respect to the end faces, for type-I phase matching. The 351.1-nm pump photons are spontaneously "split" into conjugate photons (conventionally denoted "signal" and "idler"), which are horizontally polarized. With irises (2 mm diameter) and filters (10 nm bandwidth) at our detectors, we select out the nearly degenerate pairs at 702.2 nm. Each detector consists of an RCA C30902S avalanche photodiode (APD) cooled to $-18\,^{\circ}\mathrm{C}$, whose output is fed into an EG&G-Ortec Model 583 constant fraction discriminator.

This particular light source has been well studied, and has been used previously in other investigations of fundamental quantum optical phenomena [14]. In one such configuration, the Hong-Ou-Mandel interferometer [Fig. 2(a)], the two correlated photons are brought back together by means of two mirrors, so that they impinge simultaneously on the surface of a translatable beam splitter [15]. We measure singles and coincidence rates at the output ports (using a Stanford Research Systems SR400 Gated Photon Counter). As explained in the following section, if the beam splitter is placed such that the two photons reach it essentially simultaneously (i.e., within their coherence times), interference will result, in such a way that both photons always exit the same port of the beam splitter. Thus a null in the coincidence rate appears as the path length of one of the arms is slowly scanned, even though the singles rates remain unchanged. The width of the dip [$\approx 40\ \mu$m full width at half maximum (FWHM)] is determined by the filters in front of the detectors. In practice, it was preferable to vary the relative path length using an "optical trombone" in one arm of the interferometer, thus avoiding the problem of lateral walkoff associated with translating the recombining beam splitter directly. (One can show that dispersive effects of the trombone prism have essentially no effect on the interference dip [16].) Translation of the prism was effected by a Burleigh Inchworm piezoelectric motion system; a Heidenhain optical encoder yielded a position resolution of 0.1 μm.

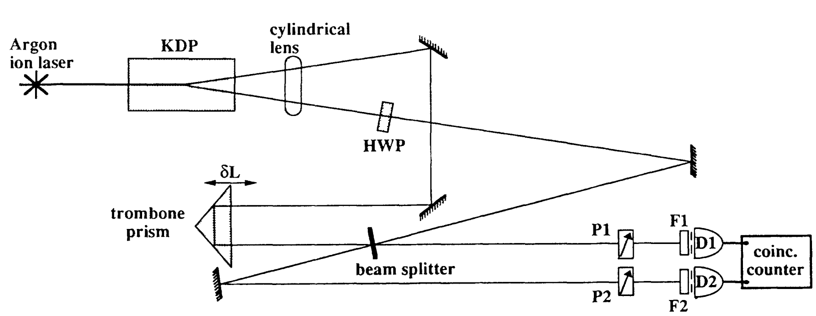

FIG. 1. Schematic of experiment to observe quantum eraser. D1 and D2 are avalanche photodiodes, P1 and P2 are polarizers, F1 and F2 are bandpass filters, and HWP is a half wave plate whose optic axis is at an angle $\phi/2$ to the horizontal polarization of the down-converted beams.

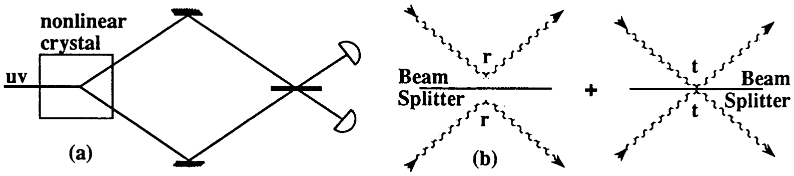

FIG. 2. (a) Simplified setup for a Hong-Ou-Mandel interferometer. (b) Feynman paths for coincidence detection.

III. HONG-OU-MANDEL INTERFERENCE

One can explain the coincidence null at zero path-length difference using the Feynman rules for calculating probabilities. The two indistinguishable processes [Fig. 2(b)] which lead to coincidence detection in the above set-up are both photons being reflected at the beam splitter and both photons being transmitted. For simplicity, suppose we have a 50:50 beam splitter, and choose the amplitude transmission coefficient to be real. The Feynman amplitudes are then $r\times r$ and $t\times t$, and the probability of a coincidence detection is

$$P_c=|r\times r+t\times t|^2=\left|\frac{i}{\sqrt{2}}\times\frac{i}{\sqrt{2}}+\frac{1}{\sqrt{2}}\times\frac{1}{\sqrt{2}}\right|^2=0\ , \tag{1}$$

where the factors of i come from the phase shift upon reflection at a beam splitter. When the path-length difference is greater than the coherence length of the photons (i.e., when the photon wave packets no longer overlap at the beam splitter), there is no such cancellation effect and coincidence events occur one half of the time, since each photon *individually* has a 50% chance of being reflected or transmitted.

More formally, we write the wave function after the beam splitter in terms of Fock states:

$$\begin{aligned}|\psi\rangle_{\Delta x=0}&=\tfrac{1}{2}[\,|1_1 1_2\rangle+i|2_1 0_2\rangle+i|0_1 2_2\rangle-|1_1 1_2\rangle]\\&=\frac{i}{2}[\,|2_1 0_2\rangle+|0_1 2_2\rangle]\ ,\end{aligned}\tag{2}$$

where the subscripts denote the propagation modes to the two detectors, and the subscript of $|\psi\rangle$ indicates zero path-length difference. As discussed in earlier works [14–17], the conjugate photons actually have a relatively broadband frequency distribution, which is determined in practice by irises and filters in front of the detectors. However, since we operate near degeneracy, and since we are considering zero path-length difference, this generalization is an unnecessary complication for our purposes. According to the standard theory of photodetection and photon correlation [18], the coincidence counting rate is given by the fourth-order correlation function

$$\begin{aligned}P_c&\approx G^{(2)}(t_1,t_2;t_2,t_1)\\&=\langle\psi|\hat{E}_1^{(-)}(t_1)\hat{E}_2^{(-)}(t_2)\hat{E}_2^{(+)}(t_2)\hat{E}_1^{(+)}(t_1)|\psi\rangle\ ,\end{aligned}\tag{3}$$

where, omitting irrelevant normalization constants, the positive- and negative-frequency field operators are defined in terms of creation and annihilation operators as

$$\hat{E}_j^{(+)}(t_j)=\int d\omega\,\hat{a}_j(\omega)e^{-i\omega t_j}$$

and (4)

$$\hat{E}_j^{(-)}(t_j)=\int d\omega\,\hat{a}_j^\dagger(\omega)e^{+i\omega t_j}\quad(j=1,2)\ .$$

We have neglected polarization for the moment, which is justified because the photons are both horizontally polarized, and our detectors are polarization independent. At zero path-length difference the integrals over frequency contribute only an overall normalization factor [19]. We can then understand the essence of the measurement described by Eq. (3) by considering the reduced operator formed by creation and annihilation operators for the two detector modes: $\hat{P}_{c,\text{red}}\equiv\hat{a}_1^\dagger\hat{a}_2^\dagger\hat{a}_2\hat{a}_1$. Clearly, $\hat{P}_{c,\text{red}}$ gives zero when it operates on $|\psi\rangle_{\Delta x=0}$, as given in Eq. (2).

When the path-length difference is greater than the coherence length of the down-converted photons ($\Delta x\gg\tau_c$), the "transmission-transmission" and "reflection-reflection" coincidence possibilities are in principle distinguishable, so they do not interfere. In this limit, we find

$$\begin{aligned}P_c(\Delta x\gg\tau_c)&\approx\frac{1}{4}\langle 1_1 1_2|\hat{P}_{c,\text{red}}|1_1 1_2\rangle\\&\quad+\frac{i^4}{4}\langle 1_1 1_2|\hat{P}_{c,\text{red}}|1_1 1_2\rangle=\frac{1}{2}\ .\end{aligned}\tag{5}$$

(The reduction by a factor of 2 reflects the fact that we are only considering *coincidence* counts, not cases where both photons go to the same detector.)

This demonstrates the coincidence dip at zero path-length difference to the beam splitter. Note that the singles rate at either detector, given by $P_s\approx G^{(1)}(t_j;t_j)=\langle\psi|\hat{E}_j^{(-)}(t_j)\hat{E}_j^{(+)}(t_j)|\psi\rangle$, does not show this dependence on path-length difference. It has been shown that as long as the visibility of the coincidence dip is greater than 50%, no semiclassical field theory can account for the observed interference [20].

IV. LOSS OF INTERFERENCE

In the spirit of the Feynman two-slit experiment, we ask if one can perform a "measurement" on the photons which will yield which-way information. Of course, we could place an APD or photomultiplier directly in one of the input arms of the interferometer, but then lack of coincidence is a trivial consequence. We consider instead what happens when a half wave plate at an angle $\phi/2$ to the horizontal is inserted into one input arm of the interferometer, as depicted in Fig. 1 (and we adjust the trombone to compensate for the optical path length of the wave plate). The polarization of the photon in that arm is then rotated by ϕ, making the two Feynman paths partially distinguishable, thereby reducing the amount of interference. The degree to which the interference is lost depends on the angle ϕ, and is calculated below. In the extreme case ($\phi/2=45°$) the polarization states of the two different photons reaching the beam splitter are orthogonal. The two paths are now *completely* distinguishable and the amplitudes are squared before being summed. The result: no interference. These effects are shown in Fig. 3(a).

In terms of our earlier formalism, we have entangled the number-state basis wave function with polarization information:

$$|\psi\rangle_{\Delta x=0}=\tfrac{1}{2}[|1_1 1_2\rangle\otimes|H_1(H+\phi)_2\rangle - |1_1 1_2\rangle\otimes|(H+\phi)_1 H_2\rangle] , \quad (6a)$$

where the notation H_j indicates that the photon reaching detector j is horizontally polarized, and $(H+\phi)_j$ indi-

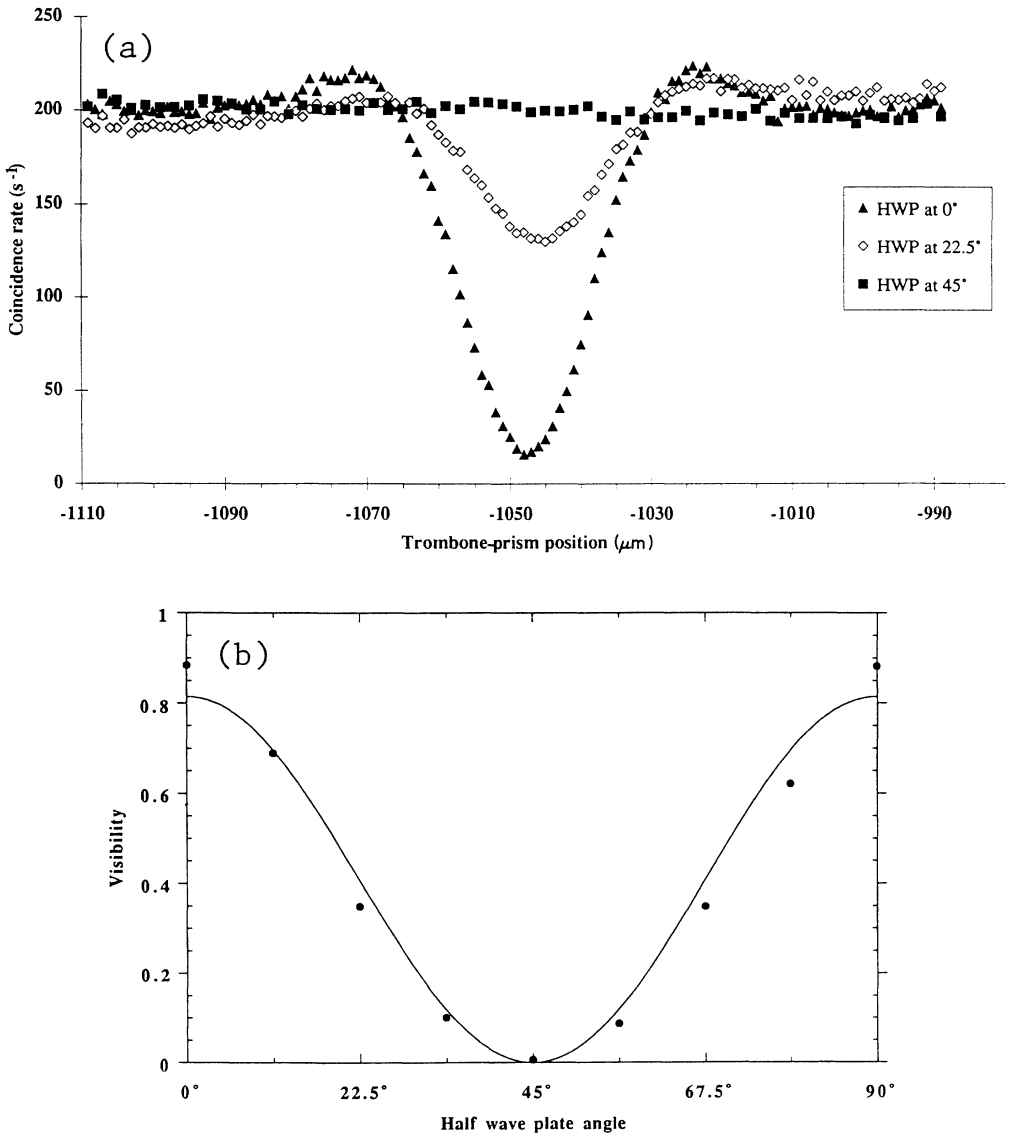

FIG. 3. (a) Profile of interference dip in coincidence rate for three wave plate orientations. (Accidental coincidences have been subtracted, and rates far from dip have been normalized to the same value.) Note that the interference effect is seen to vanish when the wave plate is at 45°, i.e., when the input ports to the beam splitter are made distinguishable. (b) Visibility as a function of half wave plate angle. The solid line is a fit to theory, with maximum visibility as the free parameter. The experimental points do not lie exactly on the same curve because slight fluctuations in alignment affect the visibility.

cates that the photon is polarized at an angle ϕ to the horizontal. We have already omitted the kets in which both photons go to the same detector, since we are interested here in coincidence rates. We introduce the following simplified notation:

$$|\psi\rangle_{\Delta x=0}=\tfrac{1}{2}[|1_1^H 1_2^{H+\phi}\rangle-|1_1^{H+\phi}1_2^H\rangle] . \quad (6b)$$

To account for polarization, the field operators may now be generalized to the vector operators $\hat{\mathbf{a}}_j^\dagger=\hat{a}_{j,H}^\dagger\epsilon_{j,H}+\hat{a}_{j,V}^\dagger\epsilon_{j,V}$ and $\hat{\mathbf{a}}_j=\hat{a}_{j,H}\epsilon_{j,H}+\hat{a}_{j,V}\epsilon_{j,V}$, where $\epsilon_{j,H}$ and $\epsilon_{j,V}$ are orthonormal polarization vectors (associated with detector index $j=1,2$) in the horizontal and vertical directions, respectively. The new reduced operator relevant for coincidence counting is then

$$\hat{P}'_{c,\text{red}}\equiv\sum_{\lambda_1,\lambda_2=H,V}a_{1,\lambda_1}^\dagger a_{2,\lambda_2}^\dagger a_{2,\lambda_2}a_{1,\lambda_1}=\sum_{\lambda_1,\lambda_2=H,V}a_{1,\lambda_1}^\dagger a_{1,\lambda_1}a_{2,\lambda_2}^\dagger a_{2,\lambda_2}$$

$$=(\hat{\mathbf{a}}_1^\dagger\cdot\hat{\mathbf{a}}_1)(\hat{\mathbf{a}}_2^\dagger\cdot\hat{\mathbf{a}}_2)=(\hat{a}_{1,H}^\dagger\hat{a}_{1,H}+\hat{a}_{1,V}^\dagger\hat{a}_{1,V})(\hat{a}_{2,H}^\dagger\hat{a}_{2,H}+\hat{a}_{2,V}^\dagger\hat{a}_{2,V}) . \quad (7)$$

Using the expansion $|1_j^{H+\phi}\rangle=|1_j^H\rangle\cos\phi+|1_j^V\rangle\sin\phi$, we find

$$P_c(0)\approx\langle\psi|\hat{P}'_{c,\text{red}}|\psi\rangle_{\Delta x=0}=\tfrac{1}{2}\sin^2\phi . \quad (8)$$

When the path-length difference is greater than the photon coherence length, the calculation of the coincidence rate proceeds as before:

$$P_c(\Delta x\gg\tau_c)\approx\frac{1}{4}\langle 1_1^H 1_2^{H+\phi}|\hat{P}'_{c,\text{red}}|1_1^H 1_2^{H+\phi}\rangle+\frac{i^4}{4}\langle 1_1^{H+\phi}1_2^H|\hat{P}'_{c,\text{red}}|1_1^{H+\phi}1_2^H\rangle=\frac{1}{2} . \quad (9)$$

The visibility of the dip, defined as $V=\{P_c(\Delta x\gg\tau_c)-P_c(\Delta x=0)\}/P_c(\Delta x\gg\tau_c)$, has the form $\cos^2\phi$. The experimental demonstration of this relationship is shown in Fig. 3(b). The lack of perfect visibility even at $\phi=0$ results from imperfect alignment of the system, so that the signal and idler modes leaving the beam splitter are already somewhat distinguishable, regardless of their polarization.

Following Scully, Shea, and McCullen [6], one can also approach the loss of interference in terms of the density matrix. When the photon-propagation states are entangled with the polarization states, the density matrix of the system is enlarged. It still represents a pure state, however, with the quantum coherence of the entanglement manifested in the off-diagonal matrix elements. The "collapse" to a mixed state occurs when we trace over the polarization degrees of freedom, i.e., when we detect the final propagation direction of the photons *irrespective of their polarization.* In this case the reduced density matrix has only diagonal elements, because the polarization states $|H_j\rangle$ and $|V_j\rangle$ (which are essentially the "environment" for our purposes) are orthogonal. This is precisely the method of decoherence recently discussed by Zurek, although he focused on an environment which was either "uncontrollable" or possessed a large number of degrees of freedom [21]. In either case, the process is effectively irreversible, which is certainly not the case in our experiment, as we shall see presently.

V. QUANTUM ERASER

The essence of the quantum eraser can be understood relatively easily now in Feynman's language of distinguishability. As we have seen, with the half wave plate at 45°($\phi=90°$) the two paths leading to coincidence detection ("reflection-reflection" and "transmission-transmission") are distinguishable; they leave the light in each port in a different polarization state. For this reason, their probabilities are to be added incoherently, and there is no interference term. What if one could erase the information carried by the polarization, thus making the final states indistinguishable? This is precisely what happens when one places polarizers oriented at 45° to the horizontal in both output ports of the interferometer. (See Fig. 1.)

Both paths can lead to coincidence detection, and to the same final state. Therefore their probability *amplitudes* are added, thus reviving the Hong-Ou-Mandel interference dip at equal path length. Note that the insertion of a polarizer in only one of the output ports is insufficient to erase the distinguishability of the final states, because the photon in the other port still possesses *welcher Weg* information. Hence the only effect of a single polarizer is to reduce both the singles and the coincidence count rate by half.

The editing accomplished with two polarizers is not limited to erasure, as can be motivated by the following observation. Regardless of the rest of the system, the light in port 2 can always be broken up into its orthogonal polarization components. But we just saw that with both P1 and P2 at 45°, the interference dip reappeared (albeit attenuated by a factor of 4). Furthermore, we argued that the coincidence profile with polarizer P1 at 45° and P2 not in place was a flat line. It is clear then that if P1 is placed at 45° and P2 is placed at −45°, instead of a dip, a peak centered at zero path-length difference will now appear. These theoretical results are presented in Fig. 4(a) and our data in Fig. 4(b). As shown below, this is merely a specific instance of a more general property of the two-photon state emitted by the interferometer. (It should be noted that the possibility of producing a *peak* at zero path-length difference greatly aids the alignment process for the Hong-Ou-Mandel interferometer.)

We now present a simplified analysis, limiting ourselves to the case $\phi=90°$. A more complete calculation is presented in the Appendix. The output of the interferometer is given by a special case of the entangled state in Eq. (6b):

$$|\psi(0)\rangle=\tfrac{1}{2}[|1_1^H 1_2^V\rangle-|1_1^V 1_2^H\rangle]\ , \tag{10}$$

where we have again dropped terms which could not lead to coincidence counts. Detection of a photon at one port

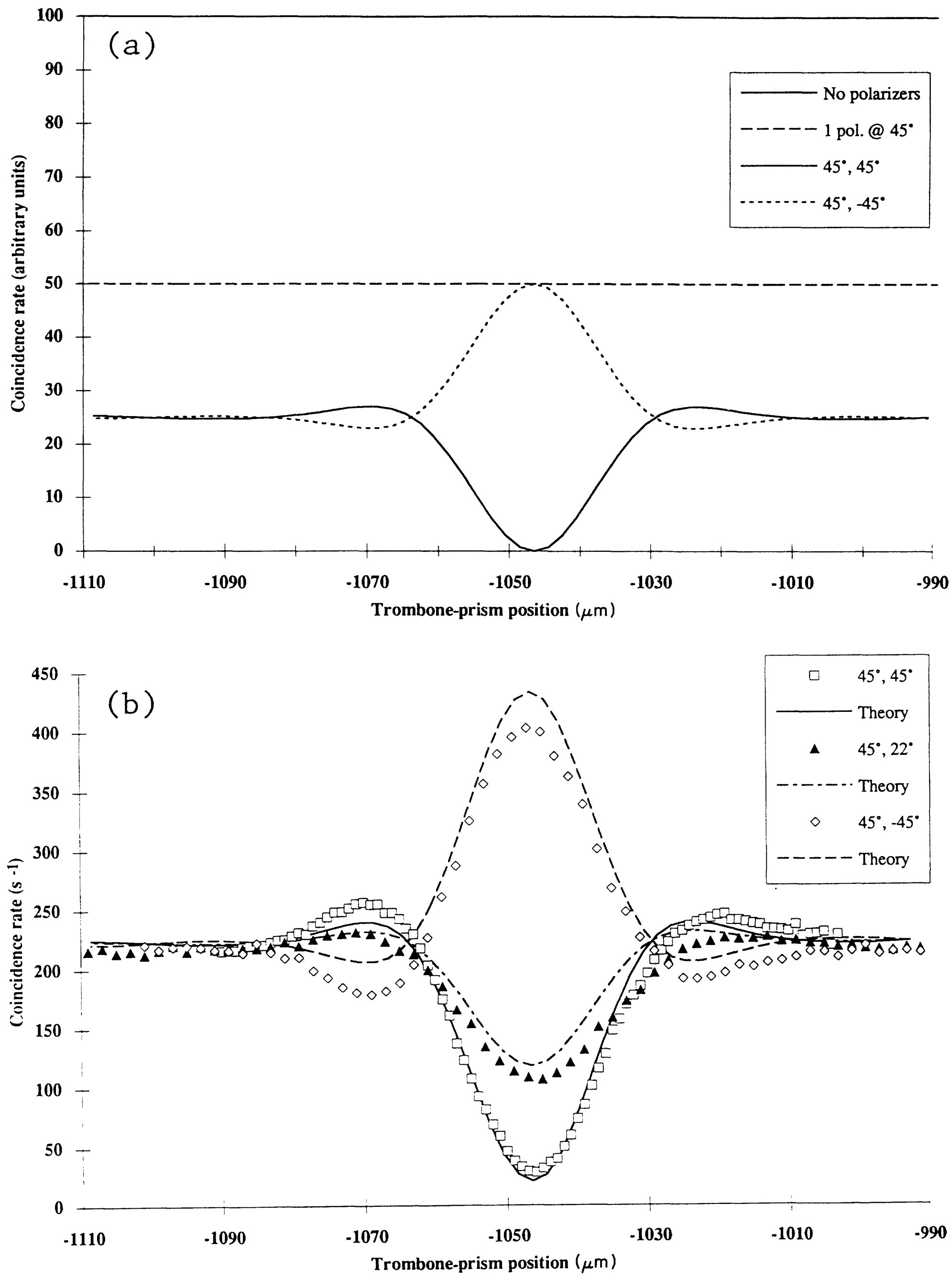

FIG. 4. (a) Theoretical curves showing how two polarizers at appropriately chosen angles can erase distinguishability, restoring an interference pattern. (b) Experimental data and scaled theoretical curves (adjusted to fit observed visibility of 91%) with polarizer 1 at 45° and polarizer 2 at various angles. Far from the dip, there is no interference and the angle is irrelevant. At the dip, the nonlocal collapse of the polarization of photon 2 causes us to observe sinusoidal variation as predicted in Eq. (13). [Normalization is the same as in Fig. 3(a).]

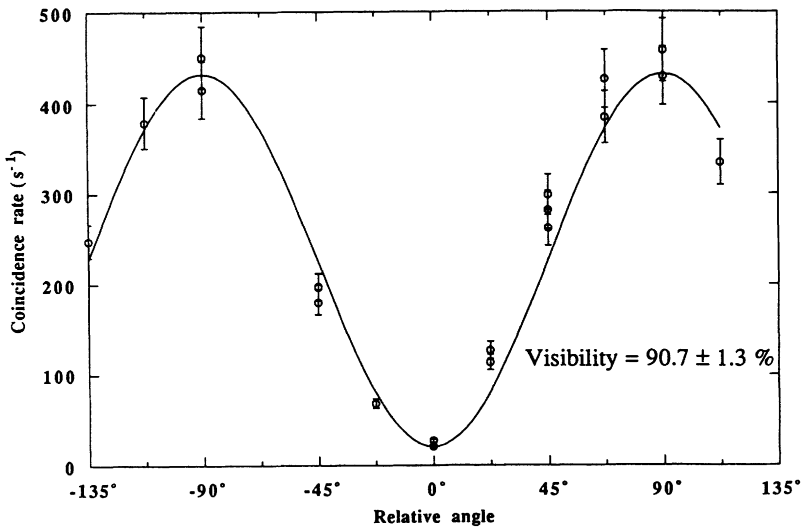

FIG. 5. Plot of coincidence rate vs relative angle of polarizers 1 and 2, corrected for accidentals. The smooth curve is a fit to theory, with visibility as a free parameter.

with no polarizer collapses the remote photon into a *mixed state* with half polarized horizontally and half polarized vertically. However, if a linear polarizer is placed at an angle θ_1 to the horizontal in output port 1, a detection event at detector 1 corresponds to a von Neumann projection in the subspace corresponding to that port onto the state vector $|\theta_1\rangle=(|1_1^H\rangle\cos\theta_1+|1_1^V\rangle\sin\theta_1)$. We are left with a pure state for the conjugate photon:

$$\langle\theta_1|\psi\rangle_{\Delta x=0}=\tfrac{1}{2}(|1_2^V\rangle\cos\theta_1-|1_2^H\rangle\sin\theta_1)\ . \qquad (11)$$

Examining output port 2 with another polarizer, we observe that the light in this mode is polarized orthogonal to θ_1; the probability amplitude is

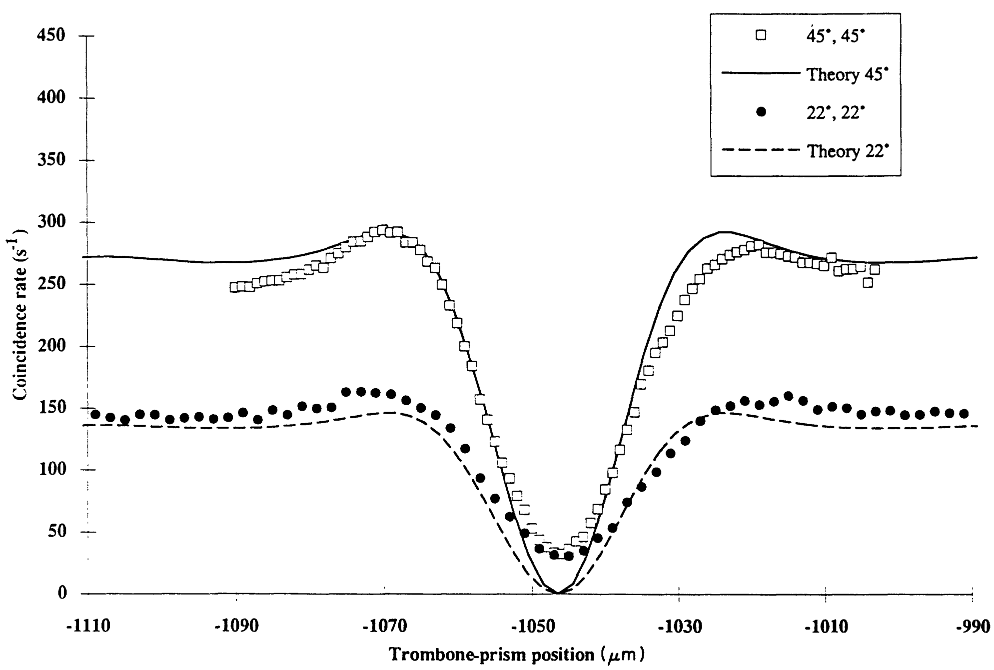

FIG. 6. Erasure also occurs, but in a somewhat different fashion, if the two polarizers are kept at the same angle and scanned towards 45°. With perfect visibility, the absolute angle would affect only the count rates far from the dip (clearly, at 0° or 90° no coincidences can ever be observed), and a total null would be observed at the dip because the two photons in the "singlet" state of Eq. (10) are always orthogonal. (The data are normalized to singles and corrected for accidentals.)

$$\langle \theta_2\theta_1|\psi\rangle_{\Delta x=0}=\tfrac{1}{2}(\langle 1_2^H|\cos\theta_2+\langle 1_2^V|\sin\theta_2)\times(|1_2^V\rangle\cos\theta_1-|1_2^H\rangle\sin\theta_1)=\tfrac{1}{2}(\sin\theta_2\cos\theta_1-\cos\theta_2\sin\theta_1)=\tfrac{1}{2}\sin(\theta_2-\theta_1)\ . \quad (12)$$

Thus

$$P_c(0)\approx|\langle \theta_1\theta_2|\psi\rangle_{\Delta x=0}|^2=\tfrac{1}{4}\sin^2(\theta_2-\theta_1)\ . \quad (13)$$

Hence the interference dip can be revived, but depending on the *relative* angle of the polarizers (see Fig. 5), it may be phase shifted and thus reappear as a peak, or any intermediate form. [Equation (13) may be recognized as a typical prediction of quantum theory when applied to certain tests of Bell's inequalities. This is hardly a coincidence, for the same nonlocal effect is responsible for both phenomena. We will discuss the relationship between our quantum-eraser experiment and similar Bell's inequalities experiments in Sec. VI.]

On the other hand, when the path-length difference is great compared with the coherence length of the photons, the probabilities for the two different paths leading to coincident detection add incoherently regardless of any polarizers:

$$P_c(\Delta x \gg \tau_c)\approx|\tfrac{1}{2}\langle \theta_1\theta_2|1_1^H1_2^V\rangle|^2+|\tfrac{1}{2}\langle \theta_1\theta_2|1_1^V1_2^H\rangle|^2=\tfrac{1}{4}\{\cos^2\theta_1\sin^2\theta_2+\sin^2\theta_1\cos^2\theta_2\}=\tfrac{1}{8}\{\sin^2(\theta_2-\theta_1)+\sin^2(\theta_2+\theta_1)\}\ . \quad (14)$$

This varies with absolute angle, in contrast to Eq. (13), since horizontal and vertical components act independently (see Fig. 6).

VI. DISCUSSION

The relationship between our experiment and other proposed quantum-eraser schemes is rather subtle. For comparison, we will focus on a particular proposal by Scully, Englert, and Walther [22], in which excited atoms are made to interfere in a two-slit–type geometry. A micromaser cavity is placed in each of the interfering paths, and prepared so that an atom passing through will decay with near certainty, leaving a photon in the cavity. For certain initial states of the cavity fields (i.e., number states), the extra photon from the decay constitutes *welcher Weg* information, and the *first*- order interference effect (fringes visible in singles detection of the atoms) is washed out. By allowing the cavity fields to subsequently interfere at a suitably placed detector, quantum erasure may be accomplished. However, as the authors stressed, this erasure is fundamentally a second-order phenomenon, in that the fringes can only be seen by *correlating* the photon counts with data stored elsewhere. In principle the decision of whether or not to erase could be postponed indefinitely, even beyond the time of detection of the atoms.

Our experiment differs somewhat from this proposal in that the basic Hong-Ou-Mandel interference effect is intrinsically a *second*-order, quantum-mechanical effect. That is, fringes are never visible in singles detection, and coincidence fringe visibility above 50% defies semiclassical explanation. While this puts the pre- and post-eraser fringes on the same footing, it has a disadvantage in that the distinguishing information we add and then erase is carried by the same photons which are to interfere. We maintain that this difference is not as fundamental as it may first appear. Although our photons themselves carry the information describing which trajectory they took, they do so only via their polarization vectors. We erase the information *after they have already left the interferometer,* and without affecting their center-of-mass wave function. In both Scully, Englert, and Walther's proposal and the present experiment, the measurement of which-way information consists of coupling the interfering particle's spatial wave function to the disjoint Hilbert space describing the *welcher Weg* detection system (e.g., micromaser cavities or photon polarization space). While this does not affect the spatial wave function, it does enlarge the Hilbert space in which it resides. It is the enlargement of the Hilbert space through entanglement, and subsequent reduction, which is the central feature of the quantum eraser.

It is useful to consider a slight gedanken variant of our experiment, which is in principle identical to it. We employ polarizing beam splitters, rather than simple polarizers, so that both polarizations may be detected. A computer then stores in one file the times of photon detection events (regardless of polarization), and in another file the polarizations of the detected photons. (Note that by making a polarization-insensitive quantum nondemolition measurement before the polarizers, one could delay the choice of polarizer orientations until after the coincident detection measurement.) Varying the orientation of the polarizing beam splitter then affects only the second file, and not the first; no interference is discernible in the first file until the data are correlated with that in the other file. As this may be performed long after the data are originally stored, we have a "delayed-choice" version of the quantum eraser.

Zajonc *et al.* have recently discussed two experiments in connection with the quantum eraser [23]. One of the experiments, while certainly a remarkable demonstration of complementarity, differs fundamentally from the quantum-eraser proposal in that it is entirely a first-order, not a second-order, interference effect. Detection events are never correlated with measurements on the "environment," and no delayed-choice version would be possible, even in principle. Their other result involves an interference effect which exists only in coincidence detection, as in our own experiment. The "'delicate' change" which leads both to distinguishability and to erasure in their example is the removal and reinsertion of a beam splitter inside the interferometer [24]. In this sense, it is not a quantum eraser since it is the structure of the interferometer itself, and not just the structure of the detection scheme, which determines once and for all the presence or absence of interference fringes.

Some of the results presented here have been observed previously by other researchers, in the context of nonlocal correlations and Einstein-Podolsky-Rosen experiments [25,26]. Our goal was to shift some of the focus to the phenomenon of quantum erasure, which is another striking aspect of quantum entanglement. The central element in many, if not most, tests of Bell's inequalities to date is the singlet state of the correlated photons [27]. Although our photons are not produced in such a state in the down-conversion process, it arises when their polarization states are entangled with their propagation modes (i.e., lower or upper arm) [28]. From this perspective, the quantum eraser and the Bell-type tests are just different approaches to investigating and understanding the character of the entangled states. One might then argue that some of the previous Bell-type tests *were* the first quantum-eraser results. However, we believe that it is important to demonstrate the loss of interference before reviving it, an aspect that, to our knowledge, has not been covered in any Bell-type experiments. Furthermore, the general goals of the two viewpoints differ. While the Bell's inequalities experiments seen to disprove the reality of local hidden variable models, the quantum eraser stresses the loss of coherence through entanglement with the "environment," and the possibility of recovering that coherence in certain circumstances.

VII. CONCLUSIONS

The quantum eraser offers an alternative perspective on interference and loss of quantum coherence in terms of (in)distinguishability of paths. Alternate paths are made distinguishable by correlating them to the "environment." Depending on how we reduce the resulting enlarged Hilbert space, we may opt to retain *welcher Weg* information and have no interference, or to reestablish indistinguishability and interference. We may make this choice long after the original interfering system has been detected, by correlating that data with the results of particular measurements on the environment with which the system was entangled. Of course, this demands that the coherence of the relevant environmental states be maintained.

Proposed experiments using atoms or neutrons, while intellectually engaging in principle, are at best very difficult in practice. We have seen that it is possible to demonstrate the essential features of the quantum eraser using a comparatively simple arrangement involving the correlated photons produced in spontaneous parametric down-conversion. The interference normally present when the two photons are superposed at a beam splitter was made to vanish when the alternate processes leading to coincidence counts were made distinguishable. For this purpose a half wave plate in one arm of the interferometer served to entangle the photon spatial wave function with the polarization subspace. Using polarizers at the output, it was then possible to restore interference, and even to alter its form.

One of the things the quantum eraser teaches us is that the state involved in interference is the *total* physical state, which in addition to photon spatial wave functions may include photon polarization, or even distant atoms with which the photons have interacted. In all realizations of the quantum eraser, the "magic" comes about through entangling the interfering system with some other degrees of freedom. The eraser "meddles" with the interference only via this entanglement, regardless of whether the extra information is stored in states of remote atoms or in the polarization components of the photonic wave functions. The process allows the introduction of an arbitrary phase between different components of the entangled state; in this sense, the phenomenon is better described as quantum *editing*.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research under Grant No. N00014-90-J-1259. We would like to thank Marlan Scully, Berthold-Georg Englert, Ivan Deutsch, and Yakir Aharonov for helpful discussions.

APPENDIX

As a preliminary to the general calculation of the quantum eraser effect, with arbitrary orientations of the half wave plate, polarizer P1, and polarizer P2, we write the effective projection operator for a polarizer at an angle θ to the horizontal, placed along the path corresponding to the propagation mode index j:

$$\begin{aligned}\hat{P}_{\mathrm{pol},j}(\theta)&=|1_j^{H+\theta}\rangle\langle 1_j^{H+\theta}|\\&=(|1_j^H\rangle\cos\theta+|1_j^V\rangle\sin\theta)(\langle 1_j^H|\cos\theta+\langle 1_j^V|\sin\theta)\ ,\end{aligned}\tag{A1}$$

where we are considering only the effect on single-photon states. It will be useful to consider the effect of this operator on a state of arbitrary polarization:

$$\begin{aligned}\hat{P}_{\mathrm{pol},j}(\theta)|1_j^{H+\phi}\rangle&=|1_j^{H+\theta}\rangle\langle 1_j^{H+\theta}|1_j^{H+\phi}\rangle\\&=(|1_j^H\rangle\cos\theta+|1_j^V\rangle\sin\theta)(\langle 1_j^H|\cos\theta+\langle 1_j^V|\sin\theta)(|1_j^H\rangle\cos\phi+|1_j^V\rangle\sin\phi)\\&=|1_j^H\rangle[\cos\theta(\cos\theta\cos\phi+\sin\theta\sin\phi)]+|1_j^V\rangle[\sin\theta(\cos\theta\cos\phi+\sin\theta\sin\phi)]\ .\end{aligned}\tag{A2}$$

For example, we can then examine the rate of single-event detection for a single-photon state, horizontally polarized, passed through a polarizer:

$$\begin{aligned}P_s\approx G^{(1)}(t;t)&=\langle\psi|\hat{\mathbf{E}}^{(-)}(t)\hat{\mathbf{E}}^{(+)}(t)|\psi\rangle\\&\approx\langle 1^H|\hat{P}_{\mathrm{pol},j}(\theta)(\hat{a}_H^\dagger\hat{a}_H+\hat{a}_V^\dagger\hat{a}_V)\hat{P}_{\mathrm{pol},j}(\theta)|1^H\rangle=\cos^4\theta+\cos^2\theta\sin^2\theta=\cos^2\theta\ ,\end{aligned}\tag{A3}$$

which is the result expected from Malus's law.

We now show that using a single polarizer, before detector D1 for instance, is not enough to revive the interference dip. Using the reduced coincidence detection operator from Eq. (7), and the entangled state of the photons from (6b), we have

$$\begin{aligned}
P_c(0) &\approx \langle \psi|\hat{P}_{\mathrm{pol},1}(\theta_1)\hat{P}_{c,\mathrm{red}}{}'\hat{P}_{\mathrm{pol},1}(\theta_1)|\psi\rangle_{\Delta x=0} \\
&= \tfrac{1}{2}[\langle 1_1^H 1_2^{H+\phi}| - \langle 1_1^{H+\phi}1_2^H|]|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|(\hat{a}_{1,H}^\dagger\hat{a}_{1,H}+\hat{a}_{1,V}^\dagger\hat{a}_{1,V}) \\
&\quad\times(\hat{a}_{2,H}^\dagger\hat{a}_{2,H}+\hat{a}_{2,V}^\dagger\hat{a}_{2,V})|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|\tfrac{1}{2}[|1_1^H 1_2^{H+\phi}\rangle - |1_1^{H+\phi}1_2^H\rangle] \\
&= \tfrac{1}{4}\sin^2\phi(\cos^4\theta+2\cos^2\theta\sin^2\theta+\sin^4\theta)=\tfrac{1}{4}\sin^2\phi\ .
\end{aligned} \tag{A4}$$

We see immediately that for $\phi=90°$, when the two paths are maximally distinguishable there is no null in coincidence for any orientation of a single polarizer at the output.

We turn now to the general case with two polarizers set at arbitrary angles θ_1 and θ_2.

$$\begin{aligned}
P_c(0) &\approx \langle \psi|\hat{P}_{\mathrm{pol},1}(\theta_1)\hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{c,\mathrm{red}}{}'\hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{\mathrm{pol},1}(\theta_1)|\psi\rangle_{\Delta x=0} \\
&= \tfrac{1}{2}[\langle 1_1^H 1_2^{H+\phi}| - \langle 1_1^{H+\phi}1_2^H|](|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|)(|1_2^{H+\theta_2}\rangle\langle 1_2^{H+\theta_2}|)(\hat{a}_{1,H}^\dagger\hat{a}_{1,H}+\hat{a}_{1,V}^\dagger\hat{a}_{1,V}) \\
&\quad\times(\hat{a}_{2,H}^\dagger\hat{a}_{2,H}+\hat{a}_{2,V}^\dagger\hat{a}_{2,V})(|1_2^{H+\theta_2}\rangle\langle 1_2^{H+\theta_2}|)(|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|)\tfrac{1}{2}[|1_1^H 1_2^{H+\phi}\rangle - |1_1^{H+\phi}1_2^H\rangle]\ .
\end{aligned}$$

Using Eq. (A2), one can expand $|\tilde{\psi}\rangle_{\Delta x=0}=\hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{\mathrm{pol},1}(\theta_1)|\psi\rangle_{\Delta x=0}$. After simplifying algebra one finds

$$\begin{aligned}
|\tilde{\psi}\rangle_{\Delta x=0} &= |1_1^H 1_2^H\rangle\cos\theta_1\cos\theta_2\sin(\theta_2-\theta_1)\sin\phi + ||1_1^V 1_2^V\rangle\sin\theta_1\sin\theta_2\sin(\theta_2-\theta_1)\sin\phi \\
&\quad + |1_1^H 1_2^V\rangle\cos\theta_1\sin\theta_2\sin(\theta_2-\theta_1)\sin\phi + |1_1^V 1_2^H\rangle\sin\theta_1\cos\theta_2\sin(\theta_2-\theta_1)\sin\phi\ .
\end{aligned}$$

It then follows that

$$P_c(0)\approx\langle\tilde{\psi}|\hat{P}_{c,\mathrm{red}}{}'|\tilde{\psi}\rangle_{\Delta x=0}=\sin^2\phi\sin^2(\theta_2-\theta_1)\ , \tag{A5}$$

which is the more general case of Eq. (13).

---

[1] R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison Wesley, Reading, MA, 1965).

[2] A. Peres, Phys. Rev. D **22**, 879 (1980).

[3] A. Stern, Y. Aharonov, and Y. Imry, Phys. Rev. A **41**, 3436 (1990). Stern *et al.* have shown a general equivalence between this interpretation and one in which the environment "scrambles" the phase of the interfering system due to an uncertain interaction potential. We find the second picture less helpful in the experiments under consideration, as the relation of this potential to the experimental system is often rather subtle. Thus we restrict ourselves here to the first interpretation.

[4] M. Hillery and M. O. Scully, in *Quantum Optics, Experimental Gravitation, and Measurement Theory,* edited by P. Meystre *et al.* (Plenum, New York, 1983), pp. 65–85.

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

[6] M. O. Scully, R. Shea, and J. D. McCullen, Phys. Rep. **43**, 485 (1978).

[7] The atom is initially polarized in the $+\hat{\mathbf{x}}$ direction, using a Stern-Gerlach apparatus (SGA) along $+\hat{\mathbf{x}}$ as a filter. An SGA measuring $\langle S\rangle$ along $+\hat{\mathbf{z}}$ acts as the first beam splitter. Two SGA's (along $-\hat{\mathbf{z}}$) act as mirrors to deflect the spin-up atoms to the recombining beam splitter, another SGA along $+\hat{\mathbf{z}}$. Similarly, two other SGA's (along $-\hat{\mathbf{z}}$) act as mirrors to deflect the spin-down atoms to the recombining beam spitter. In principle, the SGA in the second half of the interferometer may be made to reverse the effects of the SGA in the first half; the atoms after the final SGA will then be polarized in the $+\hat{\mathbf{x}}$ direction again. This may be checked by an analyzer (a second SGA along $+\hat{\mathbf{x}}$) after the interferometer.

[8] B.-G. Englert, J. Schwinger, and M. O. Scully, Found. Phys. **18**, 1045 (1988).

[9] J. Schwinger, M. O. Scully, and B.-G. Englert, Z. Phys. D **10**, 135 (1988).

[10] M. O. Scully and H. Walther, Phys. Rev. A **39**, 5229 (1989).

[11] A. Zajonc, Phys. Lett. **96A**, 61 (1983).

[12] M. G. Raymer and S. Yang (unpublished).

[13] P. G. Kwiat, A. M. Steinberg, and R. Y. Chiao, in *Proceedings of the Second Santa Fe Meeting on the Foundations of Quantum Mechanics,* edited by M. O. Scully *et al.* (World Scientific, Singapore, 1992).

[14] See, for instance, [20]; P. G. Kwiat and R. Y. Chiao, Phys. Rev. Lett. **66**, 588 (1991); C. K. Hong, Z. Y. Ou, and L. Mandel, in *Photons and Quantum Fluctuations,* Malvern Physics Series, edited by E. R. Pike *et al.* (Hilger, Bristol, 1988), p. 51–65, and references therein.

[15] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).

[16] A. M. Steinberg, P. G. Kwiat and R. Y. Chiao, Phys. Rev. Lett. **68**, 2421 (1992).

[17] R. Campos, B. Saleh, and M. Teich, Phys. Rev. A **42**, 4127 (1990).

[18] R. J. Glauber, Phys. Rev. **130**, 2529 (1963).

[19] When the path-length difference is not zero, the integrals in Eq. (4), along with those implicit in $|\psi\rangle$, determine the precise form of the interference dip as a function of path-length difference, when one integrates over the time resolution of the detectors.
[20] Z. Y. Ou, Ph.D. thesis, University of Rochester, 1990.
[21] W. H. Zurek, Phys. Today **44** (10), 36 (1991).
[22] M. O. Scully, B-G. Englert, and H. Walther, Nature **351**, 111 (1991).
[23] A. G. Zajonc, L. J. Wang, X. Y. Zou, and L. Mandel, Nature **353**, 507 (1991).
[24] They correctly point out that this beam splitter seems to have no effect on the signal photons. Careful analysis, however, shows that the signal photons *never* exhibit interference on their own, but only when detected in coincidence with the idler photons. As the beam splitter does directly affect these idlers, it must be considered as part of the interferometer.
[25] Z. Y. Ou and L. Mandel, Phys. Rev. Lett. **61**, 50 (1988).
[26] Y. H. Shih and C.O. Alley, Phys. Rev. Let. **61**, 2921 (1987).
[27] A. Shimony, *An Exposition of Bell's Theorem* (Plenum, New York, 1990), and references cited therein.
[28] Strictly speaking this is not true, as is immediately apparent from the extra terms omitted from Eq. (6), corresponding to both photons propagating to the same detector. Nevertheless, since we only detect coincidence counts, the *reduced* wave function is a singlet state (so long as the path-length difference is much less than the coherence times of the conjugate photons). In fact, other experimenters have used this exact arrangement in tests of Bell's inequalitites [25,26].

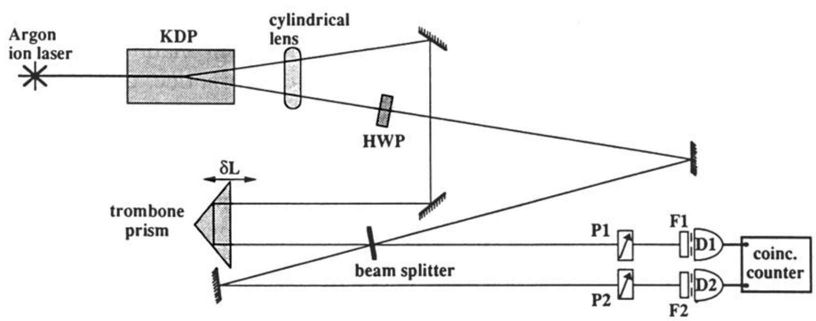

FIG. 1. Schematic of experiment to observe quantum eraser. D1 and D2 are avalanche photodiodes, P1 and P2 are polarizers, F1 and F2 are bandpass filters, and HWP is a half wave plate whose optic axis is at an angle $\phi/2$ to the horizontal polarization of the down-converted beams.