

# PHYSICAL REVIEW LETTERS

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VOLUME 84

3 JANUARY 2000

NUMBER 1

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## Delayed “Choice” Quantum Eraser

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(Received 19 January 1999)

We report a delayed “choice” quantum eraser experiment of the type proposed by Scully and Drühl (where the “choice” is made randomly by a photon at a beam splitter). The experimental results demonstrate the possibility of delayed determination of particlelike or wavelike behavior via quantum entanglement. The which-path or both-path information of a quantum can be marked or erased by its entangled twin even after the registration of the quantum.

PACS numbers: 03.65.Bz, 42.50.Dv

Complementarity, perhaps the most basic principle of quantum mechanics, distinguishes the world of quantum phenomena from the realm of classical physics. Quantum mechanically, one can never expect to measure both precise position and momentum of a quantum at the same time. It is prohibited. We say that the quantum observables “position” and “momentum” are “complementary” because the precise knowledge of the position (momentum) implies that all possible outcomes of measuring the momentum (position) are equally probable. In 1927, Bohr illustrated complementarity via the “wavelike” and “particlelike” attributes of a quantum mechanical object [1]. Since then, complementarity has often been superficially identified with the “wave-particle duality of matter.”

Over the years Young’s two-slit interference experiment has been emphasized as a good example of complementarity. Feynman, in discussing the two-slit experiment, noted that this wave-particle dual behavior contains the basic mystery of quantum mechanics [2]. The actual mechanisms that enforce complementarity vary from one experimental situation to another. In the two-slit experiment, the common “wisdom” is that the position-momentum uncertainty relation  $\delta x \delta p \geq \frac{\hbar}{2}$  makes it impossible to determine which slit the photon (or electron) passes through without at the same time disturbing the photon (or elec-

tron) enough to destroy the interference pattern. However, it has been shown [3] that under certain circumstances this common “uncertainty relation” interpretation may not be applicable. In particular, Scully and Drühl had shown how internal atomic states could be used as “which-path” markers. To be sure the interference pattern disappears when which-path information is obtained, see Ref. [4]. But it can reappear when we erase (quantum erasure) the which-path information [3]. It is interesting to note that “quantum eraser” can be combined with “delayed choice” [5]. One could even erase or mark the which-path information after the registration of the quantum and still determine its earlier behavior to be either wave or particle [6]. Since 1982, quantum eraser has been reported in several experiments [7]; however, the original scheme has not been fully demonstrated.

A quantum eraser experiment very close to the 1982 proposal (and our present experiment) is illustrated in Fig. 1. An atom labeled by *A* or *B* is excited by a weak laser pulse. A pair of entangled quanta, “photon” 1 and “photon” 2, is then emitted from either atom *A* or atom *B* by atomic cascade decay. Photon 1, propagating to the right, is registered by detector  $D_0$ , which can be scanned by a step motor along its *x* axis for the observation of interference fringes. Photon 2, propagating to the left, is injected

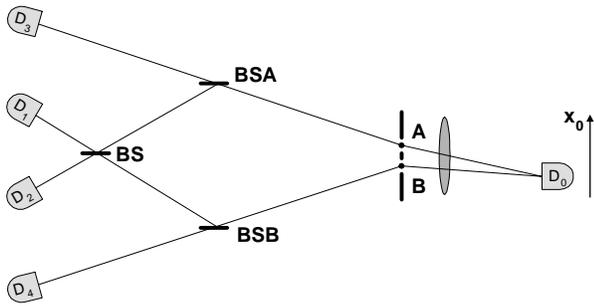


FIG. 1. Proposed quantum eraser experiment. A pair of entangled photons is emitted from either atom  $A$  or atom  $B$  by atomic cascade decay. “Clicks” at  $D_3$  or  $D_4$  provide the which-path information and clicks at  $D_1$  or  $D_2$  erase the which-path information.

into a beam splitter. If the pair is generated in atom  $A$ , photon 2 will follow the  $A$  path meeting BSA with 50% chance of being reflected or transmitted. If the pair is generated in atom  $B$ , photon 2 will follow the  $B$  path meeting BSB with 50% chance of being reflected or transmitted. In the case of the 50% chance of being transmitted at either BSA or BSB, photon 2 is detected by either detector  $D_3$  or  $D_4$ . The registration of  $D_3$  or  $D_4$  provides the which-path information (path  $A$  or path  $B$ ) of photon 2 and this in turn provides the which-path information for photon 1 due to the entanglement nature of the two-photon state generated by atomic cascade decay. Given a reflection at either BSA or BSB photon 2 continues its  $A$  or  $B$  path to meet another 50-50 beam splitter BS and then be detected by either detectors  $D_1$  or  $D_2$  shown in Fig. 1. The triggering of detectors  $D_1$  or  $D_2$  erases the which-path information of photon 1. Therefore either the absence of the interference or its restoration can be arranged via an appropriately contrived photon correlation arrangement.

The experiment is designed in such a way that  $L_0$ , the optical distance between atoms  $A$ ,  $B$  and detector  $D_0$ , is much shorter than  $L_A$  ( $L_B$ ), the optical distance between atoms  $A$ ,  $B$  and the beam splitter BSA (BSB) where the which-path or both-path “choice” is made randomly by photon 2. Thus after  $D_0$  is triggered by photon 1, photon 2 would still be on its way to BSA (BSB), i.e., the which-path or the both-path choice is “delayed” compared to the detection of photon 1. After the registration of photon 1, we look at these subsequent detection events of  $D_1$ ,  $D_2$ ,  $D_3$ , and  $D_4$  which have constant time delays,  $\tau_i \approx (L_i - L_0)/c$ , relative to the triggering time of  $D_0$ , where  $L_i$  is the optical distance between atoms  $A$ ,  $B$  and detectors  $D_1$ ,  $D_2$ ,  $D_3$ , and  $D_4$ , respectively. It is easy to see that these “joint detection” events must have resulted from the same photon pair. It is predicted that the joint detection counting rate  $R_{01}$  (joint detection rate between  $D_0$  and  $D_1$ ) and  $R_{02}$  would show an interference pattern as a function of  $D_0$ 's position on its  $x$  axis. This reflects the wave nature (both-path) of photon 1. However, no interference fringes would be observed in the joint detection counting

events  $R_{03}$  and  $R_{04}$  during the same scan of detector  $D_0$  along its  $x$  axis. This is as would be expected because we have now inferred the particle (which-path) property of photon 1. It is important to emphasize that all four joint detection rates  $R_{01}$ ,  $R_{02}$ ,  $R_{03}$ , and  $R_{04}$  are recorded at the same time during one scanning of  $D_0$ . That is, in the present experiment we “see” both wave (interference) and which-path (particlelike) with the same measurement apparatus.

Different from the early delayed choice experiments [8–10], the choice in this experiment is not actively selected by the experimentalist during the measurement. The delayed choice associated with either the wave or particle behavior of photon 1 is “randomly” made by photon 2. One simply looks at which detector  $D_1$ ,  $D_2$ ,  $D_3$  or  $D_4$  is triggered by photon 2 in order to observe either wave or particle properties of photon 1 after the registration of photon 1.

In this Letter, we report a realization of the above type of delayed choice quantum eraser experiment. The schematic diagram of the actual experimental setup is shown in Fig. 2. Instead of atomic cascade decay, spontaneous parametric down conversion (SPDC) is used to prepare the entangled two-photon state. SPDC is a spontaneous nonlinear optical process from which a signal-idler photon pair is generated when a pump laser beam is incident on a nonlinear optical crystal [11]. In our experiment, the 351.1 nm Argon ion pump laser beam is divided by a double slit and directed onto a type-II phase matching nonlinear optical crystal BBO ( $\beta$ -BaB<sub>2</sub>O<sub>4</sub>) located at regions  $A$  and  $B$ . A pair of 702.2 nm orthogonally polarized signal-idler photons is generated either from the  $A$  or the  $B$  region. The width of the SPDC slit is about

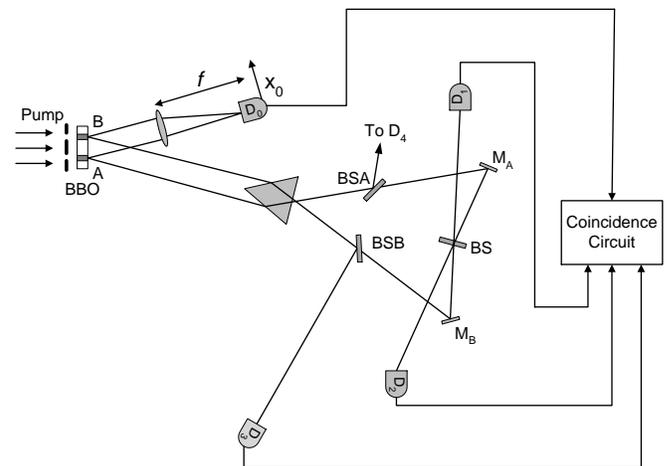


FIG. 2. Schematic of the actual experimental setup. The pump laser beam is divided by a double slit and forms two regions  $A$  and  $B$  inside the BBO crystal. A pair of signal-idler photons is then generated from either the  $A$  or the  $B$  region. The “delayed choice” to observe either wave or particle behavior of the signal photon is made randomly by the idler photon about 7.7 ns after the detection of the signal photon.

0.3 mm and the distance between the center of  $A$  and  $B$  is about 0.7 mm. A Glen-Thompson prism is used to split the orthogonally polarized signal and idler. The signal photon (photon 1, coming from either  $A$  or  $B$ ) propagates through the lens to detector  $D_0$  which is placed on the Fourier transform plane (focal plane for collimated light) of the lens. The use of the lens is to achieve the “far field” condition, while still keeping a short distance between the slit and the detector  $D_0$ . Detector  $D_0$  can be scanned along its  $x$  axis by a step motor. The idler photon (photon 2) is sent to an interferometer with equal-path optical arms. The interferometer includes a prism, two 50-50 beam splitters BSA, BSB, two reflecting mirrors  $M_A$ ,  $M_B$ , and a 50-50 beam splitter BS. Detectors  $D_1$  and  $D_2$  are placed at the two output ports of the BS, respectively, for erasing the which-path information. The triggering of detectors  $D_3$  and  $D_4$  provides the which-path information of the idler (photon 2) and in turn provides the which-path information for the signal (photon 1). The detectors are fast avalanche photodiodes with less than 1 ns rise time and about 100 ps jitter. A constant fractional discriminator is used with each of the detectors to register a single photon whenever the leading edge of the detector output pulse is above the threshold. Coincidences between  $D_0$  and  $D_i$  ( $i = 1, 2, 3, 4$ ) are recorded, yielding the joint detection counting rates  $R_{01}$ ,  $R_{02}$ ,  $R_{03}$ , and  $R_{04}$ .

In the experiment the optical delay ( $L_{A,B} - L_0$ ) is chosen to be  $\approx 2.3$  m, where  $L_0$  is the optical distance between the output surface of BBO and detector  $D_0$ , and  $L_A$  ( $L_B$ ) is the optical distance between the output surface of the BBO and the beam splitter BSA (BSB). This means that any information (which-path or both-path) one can infer from photon 2 must be at least 7.7 ns later than the registration of photon 1. Compared to the 1 ns response time of the detectors, a 2.3 m delay is thus sufficient for the “delayed erasure.” Although there is an arbitrariness in the time when a photon is detected, it is safe to say that the choice of photon 2 is delayed with respect to the detection of photon 1 at  $D_0$  since the entangled photon pair is created simultaneously.

Figures 3, 4, and 5 report the experimental results and are consistent with prediction. From Fig. 3, which shows the joint detection rates  $R_{01}$  and  $R_{02}$ , we have regained the standard Young’s double-slit interference pattern. However, there is a  $\pi$  phase shift between the two interference patterns. The  $\pi$  phase shift is explained below. In Fig. 4 the sum of  $R_{01}$  and  $R_{02}$  and the single detector counting rate of  $D_0$  are plotted for comparison.

Figure 5 reports a typical  $R_{03}$  ( $R_{04}$ ), joint detection counting rate between  $D_0$  and which-path detector  $D_3$  ( $D_4$ ). An absence of interference is clearly demonstrated. It is interesting to see that the sum of  $R_{01}$  and  $R_{02}$  is very close to that of  $R_{03}$  ( $R_{04}$ ), see Fig. 4; however, it is very different from that of the single counting rate of  $D_0$ .

To explain the experimental results, a standard quantum mechanical calculation is presented as follows. The joint

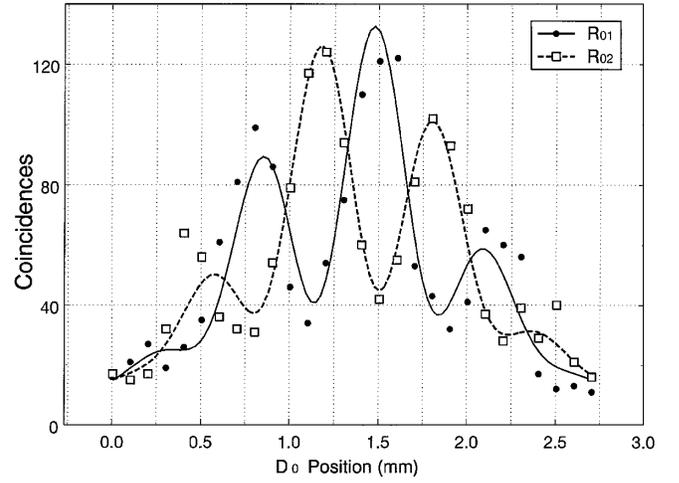


FIG. 3.  $R_{01}$  and  $R_{02}$  against the  $x$  coordinates of detector  $D_0$ . Standard Young’s double-slit interference patterns are observed. Note the  $\pi$  phase shift between  $R_{01}$  and  $R_{02}$ . The solid line and the dashed line are fits to the data based on Eq. (6).

detection counting rate,  $R_{0i}$ , of detector  $D_0$  and detector  $D_j$ , on the time interval  $T$ , as given by Glauber [12], reads

$$\begin{aligned} R_{0j} &\propto \frac{1}{T} \int_0^T \int_0^T dT_0 dT_j \langle \Psi | E_0^{(-)} E_j^{(-)} E_j^{(+)} E_0^{(+)} | \Psi \rangle \\ &= \frac{1}{T} \int_0^T \int_0^T dT_0 dT_j |\langle 0 | E_j^{(+)} E_0^{(+)} | \Psi \rangle|^2, \end{aligned} \quad (1)$$

where  $T_0$  is the detection time of  $D_0$ ,  $T_j$  is the detection time of  $D_j$  ( $j = 1, 2, 3, 4$ ), and  $E_{0,j}^{(\pm)}$  are positive and negative-frequency components of the field operators at detectors  $D_0$  and  $D_j$ , respectively.  $|\Psi\rangle$  is the SPDC entangled state,

$$|\Psi\rangle = \sum_{s,i} C(\mathbf{k}_s, \mathbf{k}_i) a_s^\dagger[\omega(\mathbf{k}_s)] a_i^\dagger[\omega(\mathbf{k}_i)] |0\rangle, \quad (2)$$

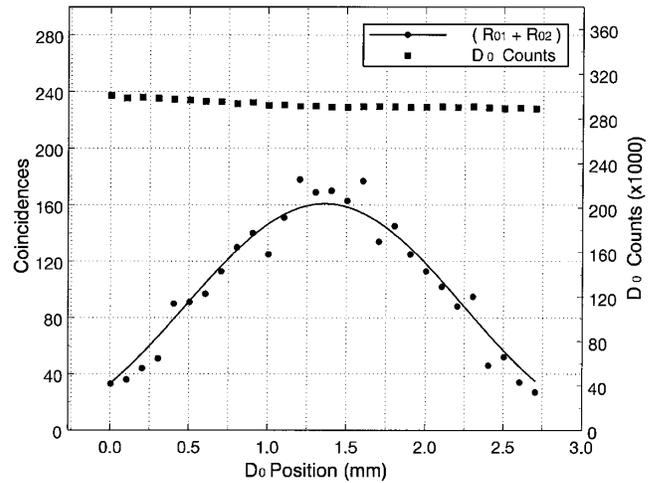


FIG. 4.  $R_{01} + R_{02}$  is shown. The solid line is a fit to the sinc function given in Eq. (6). The single counting rate of  $D_0$  is constant over the scanning range.

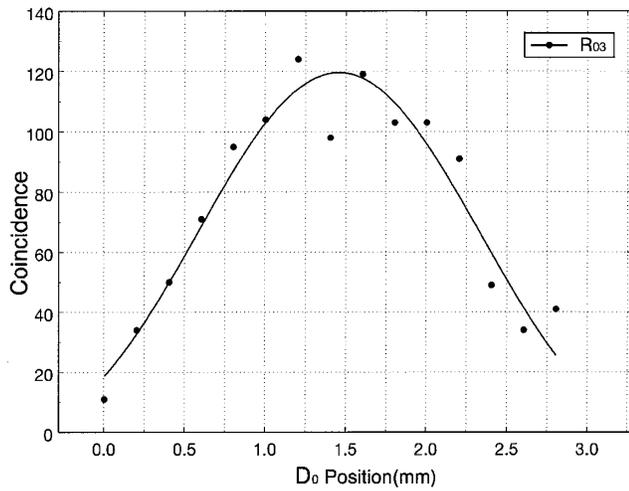


FIG. 5.  $R_{03}$  is shown. Absence of interference is clearly demonstrated. The solid line is a fit to the sinc function given in Eq. (6).

where  $C(\mathbf{k}_s, \mathbf{k}_i) = \delta(\omega_s + \omega_i - \omega_p)\delta(\mathbf{k}_s + \mathbf{k}_i - \mathbf{k}_p)$ , for SPDC in which  $\omega_j$  and  $\mathbf{k}_j$  ( $j = s, i, p$ ) are the frequency and wave vectors of the signal ( $s$ ), idler ( $i$ ), and pump ( $p$ ), respectively;  $\omega_p$  and  $\mathbf{k}_p$  can be considered as constants since the pump is a single mode laser. In Eq. (2),  $a_s^\dagger$  and  $a_i^\dagger$  are creation operators for signal and idler photons, respectively. For the case of two scattering atoms, see Ref. [3], and in the case of cascade radiation, see Ref. [13];  $C(\mathbf{k}_s, \mathbf{k}_i)$  has a similar structure but without the momentum delta function. The  $\delta$  functions in Eq. (2) are the results of approximations assuming an infinite SPDC crystal and for infinite interaction time. Let us now introduce the two-dimensional function  $\Psi(t_0, t_j)$  in Eq. (1),

$$\Psi(t_0, t_j) \equiv \langle 0 | E_j^{(+)} E_0^{(+)} | \Psi \rangle. \quad (3)$$

$\Psi(t_0, t_j)$  is the joint count probability amplitude (“wave function” for short), where  $t_0 \equiv T_0 - L_0/c$ ,  $t_j \equiv T_j - L_j/c$ , and  $L_0$  ( $L_j$ ) is the optical distance between the output point on the BBO crystal and  $D_0$  ( $D_j$ ). The four two-photon wave functions  $\Psi(t_0, t_j)$ , corresponding to four different joint detection measurements, have the following different forms:

$$\begin{aligned} \Psi(t_0, t_1) &= A(t_0, t_1^A) + A(t_0, t_1^B), \\ \Psi(t_0, t_2) &= A(t_0, t_2^A) - A(t_0, t_2^B), \end{aligned} \quad (4)$$

$$\Psi(t_0, t_3) = A(t_0, t_3^A), \quad \Psi(t_0, t_4) = A(t_0, t_4^B), \quad (5)$$

where as in Fig. 1 the upper index of  $t$  ( $A$  or  $B$ ) labels the scattering crystal ( $A$  or  $B$  region) and the lower index of  $t$  indicates different detectors. The different sign between the two amplitudes  $\Psi(t_0, t_1)$  and  $\Psi(t_0, t_2)$  is caused by the transmission-reflection unitary transformation of the beam splitter BS; see Figs. 1 and 2.

It is straightforward to show that the two amplitudes [14] in  $\Psi(t_0, t_1)$  and  $\Psi(t_0, t_2)$  are indistinguishable so that interference is expected in both the coincidence counting

rates,  $R_{01}$  and  $R_{02}$ , however, with a  $\pi$  phase shift. If we consider that “slits”  $A$  and  $B$  both have a finite width, we thus obtain the standard interference-diffraction pattern for  $R_{01}$  and  $R_{02}$ ,

$$\begin{aligned} R_{01} &\propto \text{sinc}^2(x\pi a/\lambda f) \cos^2(x\pi d/\lambda f), \\ R_{02} &\propto \text{sinc}^2(x\pi a/\lambda f) \sin^2(x\pi d/\lambda f), \end{aligned} \quad (6)$$

where  $a$  is the width of slits  $A$  and  $B$  (equal width),  $d$  is the distance between the centers of slit  $A$  and  $B$ ,  $\lambda = \lambda_s = \lambda_i$  is the wavelength of the signal and idler, and  $f$  is the focal length of the lens. We have also applied the “far field approximation.” Finally, after we take into account the finite size of the detectors and the divergence of the pump beam, the interference visibility is found to be in satisfactory agreement with observation.

For the joint detection rates  $R_{03}$  and  $R_{04}$ , the wave function in Eq. (5) (which clearly provides the which-path information) has only one amplitude and no interference is expected.

In conclusion, we have realized a quantum eraser experiment of the type proposed in Ref. [3]. The experimental results demonstrate the possibility of determining particle-like and wavelike behaviors of a photon via quantum entanglement. The which-path or both-path information of a quantum can be erased or marked by its entangled twin even after the registration of the quantum itself.

This work was supported, in part, by The U.S. Office of Naval Research, The Army Research Office, The National Security Agency, The National Science Foundation, and The Welch Foundation. M.O.S. wishes to thank R. Haden for stimulating discussions and for his interest in this problem.

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