Complementarity and the Quantum Eraser

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We present various experiments demonstrating the mutual exclusivity of observing interference and which-path information, as demanded by Bohr's complementarity principle. Using photon pairs created in parametric down-conversion, no which-path measurements need to be performed on the interfering photon itself. Instead the other photon can be used to introduce distinguishability, which consequently destroys interference. However, a suitable measurement *erases* this distinguishability and interference can be recovered.

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Feynman described the phenomenon of interference as containing "the *only* mystery" of quantum mechanics [1]: Although a quantum system can display both wavelike behavior (interference) and particlelike behavior (passage through only one of two slits), it is impossible to obtain both interference and complete "*Welcher-Weg*" (which-path) information in a single experiment. The classic example is the recoiling-slit gedanken experiment introduced by Einstein and Bohr in their discussions leading to the formulation of the complementarity principle [2]. There a particle is first sent through a movable slit placed before a double slit. Any attempt to extract which-path information from this interference experiment will degrade the contrast of the interference pattern—if one can fully determine the path, then there is no interference at all. Indeed, the interference will be lost even if one does not actually read out the which-path detector, as long as there is the mere possibility of carrying out the measurement, i.e., as long as the contributing processes are *distinguishable* in principle.

However, the loss of interference need not be irreversible if the which-path detector is itself a quantum system. Scully and co-workers proposed experiments in which the distinguishability can be *erased* by a suitable measurement on the which-path detector [3]. By correlating the results of this measurement with the detection of the initially interfering system, one once again observes interference. Furthermore, if the path information is carried by a distinct which-path detector system, the decision of whether to read out or to erase this information can be delayed for an arbitrary time, even until *after detection* of the interfering particle. This significantly extends the concept of delayed-choice experiments as introduced by Wheeler [4].

The basic elements of a "quantum eraser" are individual interfering quantum systems, a method of introducing which-path information, and a method of subsequently erasing this information in order to restore interference. Several previous experiments, all using the photon pairs produced in spontaneous parametric down-conversion, have been discussed within the context of quantum erasers [5]. There are, however, other key ingredients desirable for an *optimal* demonstration of the phenomena [6]. In this Letter we report on several new which-path and quantum-eraser realizations [7], which avoid the deficiencies of the earlier approaches. Employing different types of which-path information—polarization and timing—along with the corresponding methods of erasure, we were able to clearly demonstrate the complementary nature of particlelike and wavelike behaviors.

The basic experimental setup is shown in Fig. 1 [8]. The 351-nm light of a single-mode Ar^+-ion laser (100 mW) was directed onto a nonlinear crystal ($LiIO_3$). There a pair of photons, historically called the "signal" and "idler," can be created by spontaneous parametric down-conversion of a UV photon. Because of type-I phase matching, the photons share the same polarization, in our case vertical. For the following we consider only signal-idler pairs with wavelengths of about 633 and 789 nm, respectively. Reflecting the pump beam back into the crystal allowed a second possibility to create such a signal-idler pair. Using two more mirrors we also redirected the signal and idler modes associated with the first process back through the crystal, such that they overlapped with those of the second process. Finally, after irises and interference filters to define the modes, silicon-avalanche photodiodes were used as single-photon

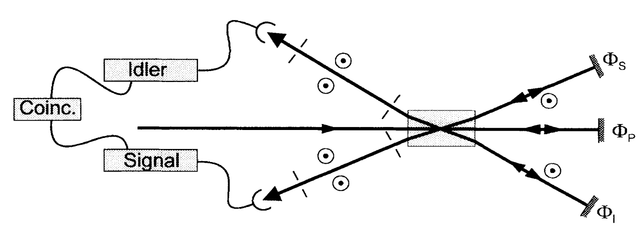

FIG. 1. Basic setup of the interferometer: A nonlinear crystal is pumped by a laser to produce photon pairs via parametric down-conversion. Directing the pump beam back through the crystal gives a second possibility to create the photon pair. Reflecting the pairs created in the first process back into the crystal makes them indistinguishable from pairs created in the second process, and interference occurs.

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detectors, with an additional time-to-amplitude converter permitting coincidence analysis (time window 5 ns) of the signal-idler pairs.

For convenience we will refer to down-conversion photons created by a pump photon in its first (second) pass through the crystal as being "reflected" ("direct"). Because of the overlap of the respective signal and idler modes, after the down-conversion crystal the reflected photons are in principle indistinguishable from the direct photons. Therefore interference occurs, as observed experimentally [8]. In particular, due to the symmetry of the experiment both the signal and idler detectors display oscillating count rates as any of the three mirrors is moved: $I_i = I_s \propto 1 + \cos\Delta\phi$, where we have defined $\Delta\phi = \phi_s + \phi_i - \phi_p$, and ϕ_s, ϕ_i, and ϕ_p denote the phases accumulated by the signal, idler, and pump beams in propagating to their respective mirrors and back [9].

The experimental arrangement affords easy access to the beam paths between the crystal and the mirrors (these distances were about 13 cm in our experiment). Thus one can manipulate the reflected down-conversion photons in such a way that they become distinguishable from those emitted directly towards the detectors. We call a device which accomplishes this a "quantum marker." In the first experiment our marker consisted of a quarter-wave plate polarization retarder in front of the mirror in the idler mode [Fig. 2(a)]. Correctly oriented, this plate rotates the polarization from vertical (V) to horizontal (H) upon double passage.

One then has the possibility to obtain which-path information for the idler photon just by measuring whether its polarization is H (a reflected idler) or V (a direct idler photon). The mere existence of this possibility demands that there cannot be any interference for the idler [Fig. 2(b)], because only processes that are indistinguishable in principle can interfere. It also demands that there cannot be any interference for the signal photon either, since the two photons are always created in pairs, and which-path information for one photon necessarily implies which-path information for the other.

However, one may erase the which-path information carried by the idler photon by measuring its polarization along 45° [Fig. 2(a)]. It is then not possible, even in principle, to tell whether a registered idler was initially H or V polarized, and the idler count rate again shows interference as any of the mirrors is moved [Fig. 2(c)]. Note that the erasure of the idler photon's path information has no influence on the detection of the signal photon and does not suffice to restore interference in the signal count rate. Put loosely, the signal photon cannot "know" how the distant idler polarizer will be oriented.

As indicated above, one should employ single particles for the interfering system in order for the which-path notion to be meaningful. Conditioned upon detection of the signal photon, the idler photon is prepared in a single-photon state [10]. Therefore, the coincidence

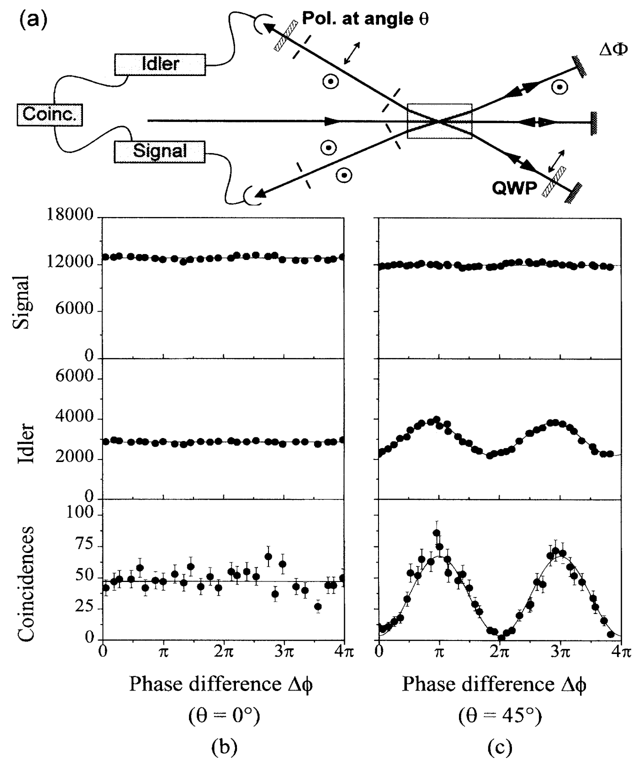

FIG. 2. (a) Experimental setup demonstrating the use of a quantum marker [quarter-wave plate (QWP)] to rotate the polarization from vertical (⊙) to horizontal (↔), and a quantum eraser (polarization analyzer). (b) Signal, idler, and coincidence count rates in the which-path measurement (polarization analysis at 0°). (c) The corresponding rates for the quantum-eraser experiment (polarization analysis at 45°). In practice the analysis was performed with a polarizing beam splitter preceded by a rotatable half wave. Here, and in the other figures, the different intensities resulted from different photon filtering. Data displayed in one column were taken in one experimental run.

detection gives the result for which-path and quantum-eraser measurements for the single idler photon [Figs. 2(b) and 2(c)], and we have fulfilled the basic requirements for a *Welcher-Weg* and quantum-eraser experiment.

Nevertheless, there are additional features that are highly desirable for an optimal demonstration of these ideas [3,6]. In particular, the which-path detection process and the resulting nonseparability become much more apparent when a system spatially distinct from the initial interfering system carries the which-path information.

We now describe two experiments where this is the case. As a starting point, consider the final configuration of the previous experiment—after the polarizer at 45° the idler photons display interference [Fig. 2(c)]. Next we introduce a quantum marker, but in the *signal* path. In the first of the two realizations we used the polarization of the signal photon as a label for marking the path.

Specifically, we inserted a quarter-wave plate in front of the mirror in the signal mode [Fig. 3(a)], thereby rotating the polarization of the reflected signal photons from V to H. Formally, this results in an entangled two-photon state right after the crystal:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|V\rangle_s|V\rangle_i + e^{i\Delta\phi}|H\rangle_s|H\rangle_i\right). \qquad (1)$$

The resulting possibility of using this arrangement for a test of Bell's inequality [11] demonstrates the close relation between the idea of the quantum eraser and the issue of nonlocality in quantum mechanics.

Using a polarizing beam splitter for the analysis of the signal photon, there are four basic measurements (in two complementary sets) on the which-path detection system. One can gain definite which-path information for the *idler* photons by measuring the *signal* polarization:

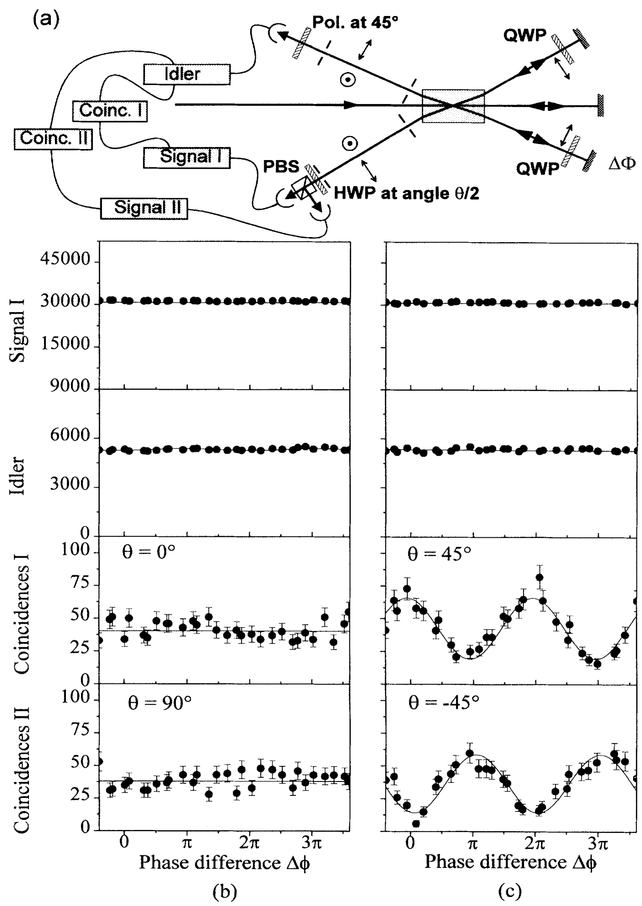

FIG. 3. (a) Experimental setup for a two-photon quantum eraser in which the signal photons carry which-path information of the interfering system, the idler photons [14]. A half-wave plate (HWP) served to rotate the polarization of the signal photon by θ. (b) Signal, idler, and coincidence count rates for a which-path measurement (analyzing the signal polarization along 0° and 90°). (c) The corresponding data after quantum erasure (analyzing the signal polarization along ±45°).

an H-polarized signal photon means a reflected idler; a V-polarized signal means a direct idler photon. Consequently, the interference in the idler singles rate vanishes [Fig. 3(b)]. However, one may erase the which-path information carried by the signal photons by means of a polarizer oriented at ±45° before the signal detector [12]. This by itself does not suffice to restore the interference for the idler count rate; if it did, one could send superluminal signals. Rather, the interference reappears only after one correlates the measurement of the signal photon with the detection of the idler photon, i.e., only in the coincidence rate [see Fig. 3(c)]. The probabilities for detecting a signal photon in coincidence with the idler photon (after its 45° polarizer) show opposite interference oscillations for the two different signal polarizations [$I(s_{+45°}) \propto 1 + \cos(\Delta\phi)$; $I(s_{-45°}) \propto 1 - \cos(\Delta\phi)$] [Fig. 3(c)]. Note that the sum of these fringes and antifringes does not display interference.

In our final experiment we started with the same quarter-wave plate and 45°-polarizer arrangement in the idler beam as before, so that interference was observable in the idler singles rate. However, we employed a different degree of freedom for labeling the signal photon: By increasing the distance between the signal mirror and the down-conversion crystal by more than the coherence length of the detected photons ($\ell_c \approx 260$ μm corresponding to a spectral width of ≈1.7 nm), we introduced the possibility to extract which-path information by measuring the relative arrival times of the photons [Fig. 4(a)]. Figure 4(b) shows a coarse scan of the signal mirror. Away from the ideal alignment ($\Delta = 0$) the interference in the idler, apparent in the large scatter of the intensity, rapidly fades away due to the in-principle temporal distinguishability. The interference disappeared even though our detectors in practice could not resolve these short time differences.

In this experiment, the erasure was accomplished by placing an interference filter with a smaller bandwidth (0.5 nm FWHM) in front of the signal detector, thus increasing the coherence length of the detected signal photons ($\ell_c \rightarrow 800$ μm) [13]. Since the resulting coherence length was then greater than the relative delay ($\Delta = 425$ μm), interference was again observed after correlating the detection of the idler photons with the registered signal photons, i.e., in the coincidence intensity [Fig. 4(c)].

In the previous two experiments, because the which-path information was carried by a quantum system (the signal photon) spatially distinct from the initially interfering system (idler photon), we can extend Wheeler's delayed-choice proposal [4]. Whereas in his proposal the interference or which-path decision had to be made before the particle had left the interferometer, here we can delay this decision (i.e., how to analyze the signal photon) until after the idler photon has been *detected*, clearly an *irreversible* process. Again, the results of the measurement only appear upon coincidence detection, however.

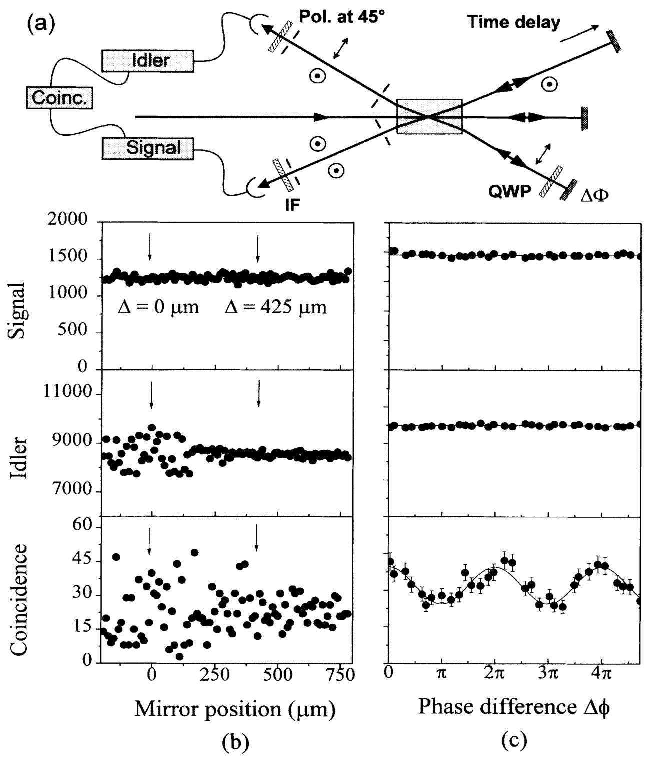

FIG. 4. (a) Experiment employing time delay as a quantum marker and a narrow-bandwidth interference filter in front of the signal detector as the quantum eraser. (b) Coarse scan of the signal mirror, showing the loss of interference for the idler photons at large Δ. The narrow-bandwidth filter in the signal beam preserves interference in the coincidence rate. (c) Phase scan for $\Delta = 425\ \mu$m.

It is straightforward to implement such a delayed-choice measurement in our experiments. For example, in our second experiment one could use an optical fiber to delay the signal photon's arrival at the *Welcher-Weg* or quantum-eraser analyzer. A fast polarization rotator (e.g., Pockels cell) before the polarizing beam splitter could then be used to switch from which-path detection (analysis along H or V) to path-information erasure (analysis along $\pm 45°$) at any arbitrary time.

In the experiments presented here, we used photon pairs together with different types of quantum markers to perform which-path and quantum-eraser operations. Note that our markers and erasers allow continuous variation of the degree of obtainable *Welcher-Weg* information, thus causing a continuous loss of interference, in agreement with Bohr's complementarity principle. The use of mutually exclusive settings of the experimental apparatus implies the complementarity between complete path information and the occurrence of interference. In conclusion, our results corroborate Bohr's view that the whole experimental setup determines the possible experimental predictions.

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[12] The passage through a polarizing beam splitter does not constitute a measurement of the polarization—one could always recombine the output beams in another beam splitter to change the analysis basis. Similar issues arise in other quantum erasers as well. Only after an *irreversible registration* of the photon should one speak of a measurement having been performed.
[13] Actually, the measurement of either photon through a narrow-bandwidth filter "collapses" the spectral bandwidth of the conjugate photon, thus increasing *its* coherence length as well.
[14] For this specific experiment the wavelengths of signal and idler photons were interchanged with respect to Fig. 2 for practical reasons.