Exploring Quantum Mechanics One Photon at a Time: A Quantum Eraser Experiment for Undergraduates

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PNACP Meeting 2016
Motivation

• Quantum mechanics lecture courses rarely have a lab component

• Student labs on quantum mechanics often focus on the “old quantum theory,” in particular, energy quantization (hydrogen spectrum, photoelectric effect, Franck-Hertz effect, etc.)
Motivation

• The **modern way** of thinking about quantum mechanics is underrepresented: qubits, quantum information, entanglement, Bell tests, quantum eraser, quantum tomography, quantum cryptography, weak measurement, etc.

• As a result, students often do not fully recognize the **essential features** of quantum mechanics

• Delayed-choice quantum eraser as an excellent **pedagogical tool**
Motivation

- **Photons** make for handy and versatile two-state quantum systems (qubits)

- Experimental equipment is **affordable**

- Can be set up and operated by **undergraduates**

- **Modular structure** of the setup means it can be used for countless modern quantum experiments

  Examples: Single-photon interference, proof of photons, Bell test, quantum tomography, quantum cryptography, quantum random number generator, weak measurement, etc.

- Adds experimental component to **lecture courses** on quantum mechanics

- **Empowers** students and faculty alike
our findings in Sec. IV and report results in Sec. V.

We describe our experimental setup in Sec. II. We first perform a theoretical analysis of the quantum eraser and then carry out the experiment, this choice is delayed until after the photon has already passed the first beamsplitter. By virtue of two mirrors (M), the paths P_1 and P_2 are placed as shown. Then for each photon sent through the Mach–Zehnder interferometer shown in Fig. 1. Photons are registered by detectors D_1 and D_2. Photons are incident on a 50–50 beamsplitter (denoted BS_1) in or out have come by one route, or by both routes after it already entered the interferometer. According to Wheeler:

"... we have a choice thought experiment based on a Mach–Zehnder interferometer. A photon passes through the 50–50 beamsplitter BS_1. As a second 50–50 beamsplitter BS_2 is inserted or removed at location O, a proof of the existence of photons, the second beamsplitter [in or out have] come by both routes. ..."
Delayed-choice interferometry

John Wheeler (1911–2008)
Delayed-choice interferometry

In Wheeler’s words:
Thus one decides whether the photon “shall come by one route, or by both routes” after it has “already done its travel.” ... We have a strange inversion of the normal order of time. We, now, by moving the mirror [in our example, the second beamsplitter] in or out have an unavoidable effect on what we have a right to say about the already past history of that photon.

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Niels Bohr’s “solitary and pregnant sentence” (Wheeler):
It obviously can make no difference as regards observable effects obtainable by a definite experimental arrangement, whether our plans of constructing or handling the instruments are fixed beforehand or whether we prefer to postpone the completion of our planning until a later moment when the particle is already on its way from one instrument to another.
Ancilla encodes “which-way information” (making the two paths distinguishable, in principle).

This precludes observation of interference.

Consequence of quantum correlations (entanglement) with the ancilla.

\[
|\Psi(x)\rangle = \frac{1}{\sqrt{2}} \left( \psi_1(x)|1\rangle + e^{i\Delta \phi} \psi_2(x)|2\rangle \right)
\]
Quantum erasure

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Quantum erasure

Measure ancilla to “erase” which-way information.

Provides additional information to decompose data into two out-of-phase interference patterns.

Erasure can be delayed until after photon has already been detected.
Quantum erasure using photons

Initial state:

\[ |\psi\rangle = (|H\rangle + |V\rangle) \sqrt{2} \]

After passage through interferometer:

\[ |\psi'\rangle = \frac{1}{\sqrt{2}} (|H\rangle + e^{i\phi} |V\rangle) \]

Measure in “diagonal” basis:

\[ |\pm 45^\circ\rangle = (|H\rangle \pm |V\rangle) / \sqrt{2} \]

\[ p(+45^\circ) = |\langle +45^\circ |\psi'\rangle|^2 = \cos^2 \frac{\Delta \phi}{2}, \]

\[ p(-45^\circ) = |\langle -45^\circ |\psi'\rangle|^2 = \sin^2 \frac{\Delta \phi}{2}. \]
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After passage through interferometer:
\[ |\Psi'\rangle = \frac{1}{\sqrt{2}} \left( |H\rangle |H\rangle + e^{i\Delta\phi} |V\rangle |V\rangle \right) \]

\[ p(+45^\circ, H) = \frac{1}{4} \]
\[ p(+45^\circ, V) = \frac{1}{4} \]
\[ p(+45^\circ, +45^\circ) = \frac{1}{2} \cos^2 \frac{\Delta\phi}{2} \]
\[ p(+45^\circ, -45^\circ) = \frac{1}{2} \sin^2 \frac{\Delta\phi}{2} \]
The experiment

Photon production:
- Polarization-entangled photon pairs (810 nm) from spontaneous parametric downconversion
- Heralded single photons using coincidence counting

Interferometer:
- Calcite beam-displacing prisms

Detectors:
- Single-photon counting modules based on avalanche photodiodes (educational model through ALPhA)

Readout:
- Field-programmable gate array, LabView

Shopping list:
- http://people.whitman.edu/~beckmk/QM/

TOTAL: $25,000–$30,000
Results (without delayed choice)

FIG. 4. (Color online) Coincidence counts $N_{AB}^{(\uparrow)}$ and $N_{A0B}^{(\downarrow)}$ as a function of the position of the actuator that adjusts the path-length difference between the two arms of the interferometer. The data in the left column are obtained when the which-way information is erased, revealing interference. The data in the right column show the absence of interference observed when the which-way information is not erased. The rows denote: (a) Without delay. (b) Free-space delay. (c) Fiber delay.

Delayed choice, we observe interference fringes with a visibility between 72% and 75% when the idler HWP is set to 22.5° (erasure). The phase shift of 180° between the two interference patterns represented by $N_{AB}^{(\uparrow)}$ and $N_{A0B}^{(\downarrow)}$ is clearly seen. Note the significantly lower count rates with the free-space delay (Fig. 4b). We attribute this effect to the presence of the additional mirrors used to elongate the optical path, leading to a widening of the idler beam during its travel between the mirrors and thus to a reduction of the number of idler photons reaching the collection lenses. Indeed, we find the singles counts in the idler arm to be about seven times smaller than in the signal beam, while in the absence of the mirrors the singles counts in both arms are within 15% of each other. We also find that the spacing of the interference fringes as a function of the actuator position is constant. Thus, we can conclude that, over the actuator's tilt range used in the experiment, a change in the position of the actuator translates into a proportional change of the relative path length inside the interferometer. The overall difference...
A converted pair of photons was produced. This results in horizontally polarized 810-nm photons, which are produced by using a half-wave plate (HWP). The pump polarization produces pairs of horizontally polarized 810-nm photons, while the other crystal produces pairs of vertically polarized 810-nm photons. Typically, a pair of stacked, 0.5-mm-thick BBO crystals is used to produce these photons through spontaneous parametric type-I downconversion.

The experimental arrangement of our quantum eraser setup is nearly identical to the one described by Beck et al., with a few modifications. To make the present paper self-contained, we will nevertheless describe the main differences. The equipment and techniques used by Beck were carried out.

In practice, the two components of the entangled state, the signal and idler, can be destroyed and the information necessary to construct an interference pattern can be irretrievably lost. This is the case for a comprehensive parts list).

The boxes delineate the different stages of our experimental setup. The signal arm and the idler arm are shown separately, with the signal beam and idler beam labeled accordingly. The pump laser is shown entering the setup, and the downconversion crystal (DC) is shown at the center. The interference of the signal and idler photons is shown, with the interferometer and polarization manipulators indicated.

Additional distance: 2.0 meters
Delay time: 6.7 ns
Results (with free-space delay)

FIG. 4. (Color online) Coincidence counts $N_{AB}$ (\(\leftrightarrow\)) and $N_{A0B}$ (\(\bullet\)) as a function of the position of the actuator that adjusts the path-length difference between the two arms of the interferometer. The data in the left column are obtained when the which-way information is erased, revealing interference. The data in the right column show the absence of interference observed when the which-way information is not erased. The rows denote: (a) Without delay. (b) Free-space delay. (c) Fiber delay.

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A polarization-entangled state, converted pair of photons was produced. This results in impossible to resolve in which of the two crystals a down-of the crystals and their close stacking means that, from is adjusted to equally pump both crystals. The thinness produces pairs of horizontally polarized 810-nm photons, while the other crystal vertically polarized 810-nm photons, and we refer the reader to these references for additional details (see especially the website). In particular, the core parts—the downconversion process, the interferometer, polarization manipulation, and its optic axes of the two crystals are oriented at 90° with respect to each other. One crystal produces pairs of very-lightly correlated the results of two separate measurements, one indicator for the quantum eraser of Ref. To make the present paper self-contained, we will not depend on whether we first measure the signal or the idler—but the choice between interference and path correlation statistics on one system by measuring its entangled signaling principle: We cannot influence the measurement. Entangled 810-nm photon pairs are produced through spontaneous parametric type-I downconversion using a pair of stacked, 0.5-mm-thick BBO crystals (cut with X). In practice, the two components are typically not perfectly indistinguishable, leading to a degradation of the entanglement. One cause is the temperature homogeneity in the idler arm (see Fig. 3) or by increasing the length of the gating the optical path after the downconversion crystal in the idler arm) and transmitted via fiber-optic cables to the idler beam (see Fig. 3). A delay of the erasure measurement is implemented alternatively by elongating fiber-optic cable to detectors. 

Additional distance: 4.0 meters
Delay time: \(\sim 20\) ns
Results (with cable delay)

FIG. 4. (Color online) Coincidence counts $N_{AB}$ (•) and $N_{A0B}$ (⌫) as a function of the position of the actuator that adjusts the path-length difference between the two arms of the interferometer. The data in the left column are obtained when the which-way information is erased, revealing interference. The data in the right column show the absence of interference observed when the which-way information is not erased. The rows denote: (a) Without delay. (b) Free-space delay. (c) Fiber delay.

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Not one of the seven delayed choice experiments [presented in the paper] has yet been done. There can hardly be one that the student of physics would not like to see done.

Concluding remarks:
How to interpret delayed-choice quantum erasure (and how not to)

• Measurement of **signal photon alone** never shows interference. Statistics are independent of whatever we do to the idler photon.

• The **temporal order** of measurements on different systems (or degrees of freedom) is **irrelevant** to the resulting statistics, even if the systems are entangled.

• Thus, quantum erasure **does not require** any “spooky action at a distance” (Einstein) or “inversion of the normal order of time” (Wheeler).

• Erasure corresponds to a **“sorting”** (or “tagging”) of the data from the interferometer using the **additional information** gained from the erasure measurement.
Acknowledgments

• UP research students:
  James Ashby, Peter Schwarz

• Equipment advice & helpful discussions:
  Mark Beck (Whitman College)
  Richard Haskell, Theresa Lynn (Harvey Mudd)
  Gabe Spalding (Advanced Laboratory Physics Association)
  Shannon Mayer (Univ. of Portland)

• Funding:
  Department of Physics, Univ. of Portland
  Student Summer Science Scholar program of the University of Portland
  Foundational Questions Institute

• Journal reference: