Delayed-Choice Interference Experiment for the Entangled-Photon Undergraduate Laboratory

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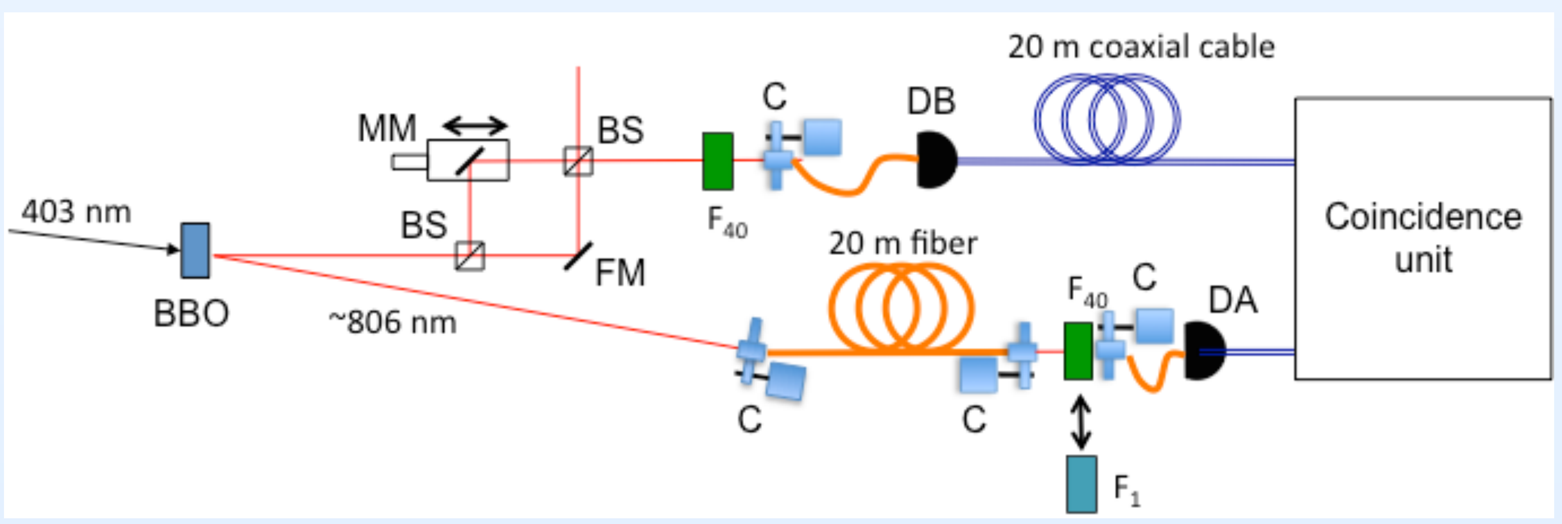
Abstract

- **Goals**:
  - To create a lab that fosters a deeper understanding of quantum physics and the predictions of quantum mechanics.
  - To gain a deeper understanding of quantum entanglement.
  - To get a better understanding of the photon.
- **Method**: To do a lab that poses an apparent paradox forces discussion.
- **Upshot**: We describe a quite feasible experiment that demands only a minor modification of a standard undergraduate lab on the quantum eraser.

Apparatus



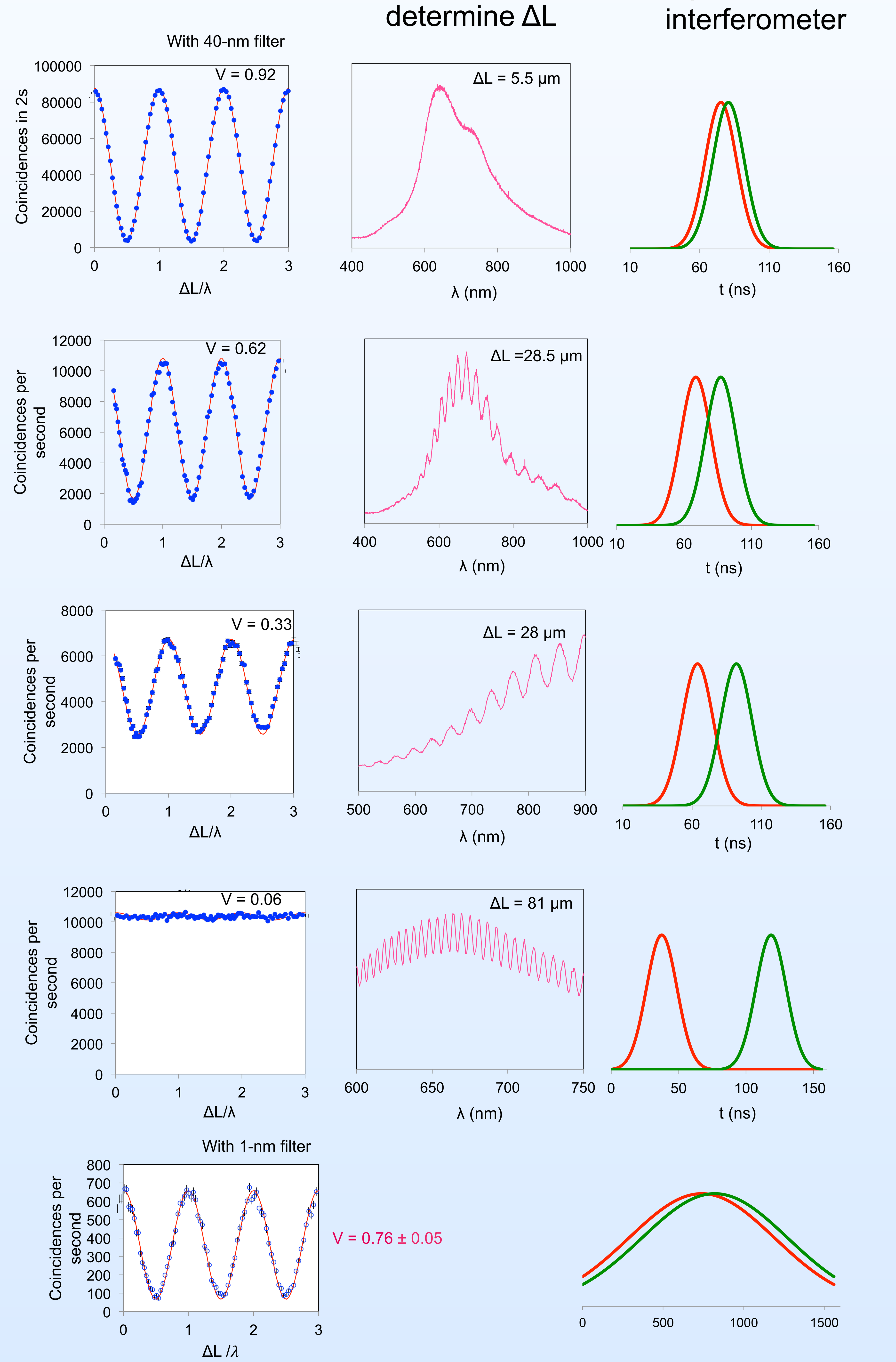
BBO: 1 type-I down-conversion crystal; BS: beam splitter; MM: movable mirror; FM: fixed mirror; DA, DB: photon detectors; C: fiber collimators; F_{40}: filter with 40nm bandwidth; F_1: filter with 1-nm bandwidth.

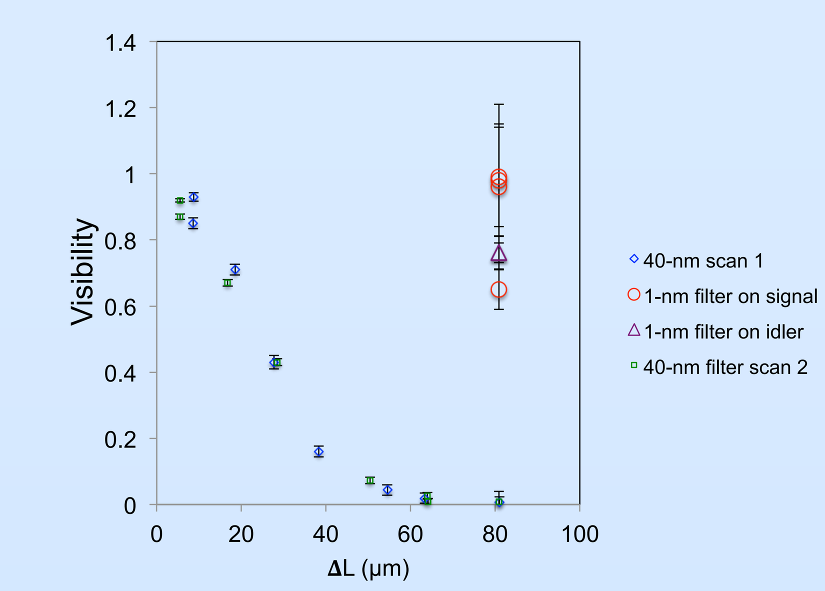
The Experiment

- Photon pairs are produced by spontaneous parametric down-conversion. They are entangled in energy.
- One photon goes to an interferometer, through a filter and to a detector. The electronic pulse (50 ns duration) travels through a 20-m cable such that it arrives at the coincidence unit 100 ns later.
- The other photon goes straight to a collimator, then through a 20-m fiber. By the time the photon goes through a band-pass filter after the fiber, the other photon has been detected and no longer exist.
- The two electronic pulses arrive at the coincidence unit at the same time.
- The difference in path length ΔL of the interferometer is increased finely to record interference, and in larger steps, comparable to the coherence length of the light.
- When the filters on the two detectors have a 40-nm bandwidth, the coherence length is 16 μm.
- The path length ΔL is increased to 80 μm. Interference disappears.
- The 40-nm filter is replaced by a 1-nm filter on the photon that does not go through the interferometer. Interference reappears.
- The *choice* to see interference occurs after the photon left the interferometer and was detected.

Data

"Single"-photon interference scans | White-light spectrum of interferometer to determine ΔL | Modeled photon wavepacket after the interferometer





Initial state:

$$|\psi\rangle = \int A(E)\,|E\rangle_1 |E_0 - E\rangle_2\, dE \qquad (1)$$

After the interferometer (un-normalized):

$$|\psi'\rangle = \int A(E)\, rt\left(1+e^{i2\pi E\Delta L/hc}\right)|E\rangle_1 |E_0 - E\rangle_2\, dE \qquad (2)$$

Probability:

$$P = \int A(E)\left|a_{40}\langle E|_1\, a_1\langle E_0 - E|_2 |\psi'\rangle\right|^2 dE \qquad (3)$$

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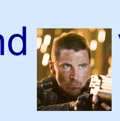
Interpretation

- The choice of filter decides whether the photon acts like a wave or a particle.
- But this choice is done by the idler photon after the signal photon is detected (dead).
- Huh? Did we send  to kill  and  vanishes?
- Not so: the photons are in an entangled state (1).
- In QM, the measurement of each photon can occur at any time; the results are the same irrespective of when the measurements are made (2).
- When the signal photon is detected, both particle and wave information are stored in the data. When the second photon is detected, its filter decides which type of information we select to have available (via coincidences).
- We leave student to confront these issues for a deeper understanding of quantum mechanics, what it predicts, and what it does not.
- J.A. Wheeler: "No phenomenon is a phenomenon until it is an observed phenomenon."