Experiment 6 - Quantum Mechanics and Quantum Optics: Single Photon Interference and the Quantum Eraser

References:

"Comparing quantum and classical correlations in a quantum eraser," by A. Gogo, W. D. Snyder, and M. Beck, *Physical Review A* **71** 052103 (2005). This is an excellent paper from Mark Beck's group at Whitman College describing a quantum eraser experiment that also involves single photon interference. We should be able to repeat this experiment with our own advanced lab setup. A hardcopy of this paper is provided in a 3-ring binder in the lab.

I. Introduction

During the Fall of 2010, Advanced Lab students completed the assembly of the polarization interferometer described by Mark Beck's group in their 2005 paper (*Phys. Rev. A* **71** 052103 (2005)). The interferometer was placed in the signal path of our experimental setup, and in early December, 2010, Aggie Szymanska (HMC '11) and Alex Baum (POM '11) were able to generate single photon interference fringes. Aggie and Alex did not have the benefit of motorized actuators to vary the path length difference for the two paths through the interferometer, so their achievement must be considered a true *tour de force*! They varied the path length difference manually, and in the process defined a new unit of small angular displacement, the "tiny turn"! Aggie and Alex made a valiant attempt to erase the fringes by rotating the 810 nm half-wave plate in the idler path, but the reduction in fringe amplitude was far from complete.

We now have a closed-loop motorized actuator that is capable of changing the path length difference in a precise, repeatable way, and the actuator has been installed on a kinematic mount holding the second of the two beam-displacing prisms comprising the interferometer in the signal path. During the Summer of 2011, Alex An (HMC '14) wrote a LabVIEW vi that incorporates control of the actuator into the acquisition of coincidence count rates using the NIM electronics. In Advanced Lab during the Fall of 2011, Robert Hoyt and Shaun Pacheco (HMC '12) performed some checks on the quantum eraser experimental setup, and then Susanna Todaro and Theo DuBose (also HMC '12) attempted to observe the presence or absence of single photon interference fringes to demonstrate the principles of a quantum eraser. They were unsuccessful – no fringes were observed.

In Optics Lab during the Spring of 2012, most activity focused on tests of Bell's inequality, but as a tech report project, Lucas Brady and Eric Anderson (HMC '13) took a shot at observing fringes with the quantum eraser setup. They too were unable to observe the expected fringes. Finally, in Advanced Lab during the Fall of 2012, Jesse Streitz (HMC '13) acted on a tip from Mark Beck who just happened to be visiting Mudd with his daughter. Mark suggested that the optical spectrum of the down-converted 810 nm entangled photon pairs may be broader than we thought, and hence the coherence length is shorter than we thought, so Jesse extended her search over a larger range of path length differences in the polarization interferometer in the signal arm. And *Voila!!* Fringes were found! During the installation of the motorized actuator, the path length difference in the interferometer had been changed by about 1.5 mm, so a more aggressive scan was needed to reach the equal path length position of the interferometer. Jesse and later Robert Kealhofer (HMC '13) were able to rotate the idler 810 nm half-wave plate and significantly reduce the amplitude of the fringes, but like all their predecessors, the fringe amplitude was far from zero. In Optics Lab in the Spring 2013, the fringes were lost when the motorized actuator was bumped, but Alex An (HMC `14) and Carola Purser (HMC `13) managed to find them once again! Like researchers before them, Alex and Carola were not able to cleanly zero the fringes by adjusting the idler 810 nm half-wave plate. Clearly there remains a challenge to be answered, and the key may be in the relative numbers of horizontally versus vertically polarized entangled photon pairs. Alex An continued his work in the fall of 2013, and began to identify several polarization-sensitive elements in the beam path that may be responsible for the problem. We are close to a working quantum eraser, but still a bit of work to do! In Section II we will describe the experimental setup in more detail, and explain how the setup constitutes a quantum eraser!

II. The Experimental Setup

The experimental setup for generating single photon interference fringes is sketched in Fig. 4-1. The entangled photon-pair source is comprised of a 50 mW violet laser (405 nm) illuminating a pair of beta-barium borate (BBO) crystals cut to facilitate type-I spontaneous parametric down-conversion (SPDC). In this non-linear process an occasional incident 405 nm photon is converted into a pair of 810 nm photons with linear polarization orthogonal to the linear polarization of the incident beam. The 405 nm half-wave plate provides a means for rotating the polarization of the incident beam so that roughly equal numbers of horizontally and vertically polarized 810 nm photons are produced in the SPDC process. Conservation of momentum and energy imposes constraints on the two 810 nm photons, so that they are entangled in energy, momentum, and polarization. An 810 nm photon in the bottom path of Fig. 4-1 is often called an “idler” photon and is used as a gate for coincidence circuitry, while an 810 nm photon in the top path is called the “signal” photon. In our work in producing single photon interference fringes, we may refer to idler photons as “gate” (G) or “gate-prime” (G') photons, depending on which detector receives them in the idler path. The signal photons may also be called “transmit” or “reflect” photons, depending on which detector receives them in the signal path. The “gate” and “transmit” and “reflect” nomenclature is a remnant of using this setup for the test of the quantum nature of light.

The pair of BBO crystals (SPDC crystals) in Fig. 4-1 consists of two 0.5 mm-thick crystals rotated so that their crystal axes are effectively perpendicular, and then cemented together. The result is that a horizontally-polarized 405-nm photon incident upon one crystal can generate a pair of entangled 810 nm photons with their polarization vertical, while a vertically-polarized 405 nm photon incident upon the other crystal can generate a pair of horizontally-polarized photons. A couple of meters down-stream of the

BBO crystals, where the detectors are located, it is impossible to tell where the photon pair was created because, even in principle, there is insufficient depth resolution looking back at the BBO crystals to place the origin of the photon pair in one crystal or the other. Hence the photons are entangled with respect to polarization as well as momentum and energy.

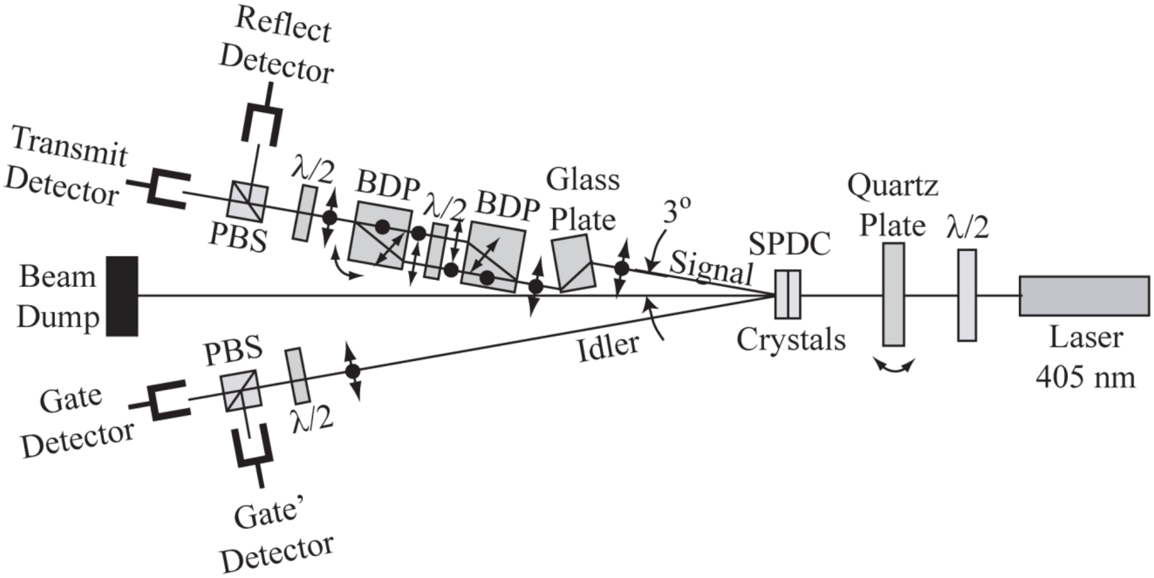

Fig. 4-1. Top view of the experimental setup for generating single photon interference fringes and demonstrating the principles of a quantum eraser. The quartz plate can be rotated about a vertical axis to zero the phase ϕ in the QM state for the entangled photon pairs. SPDC = spontaneous parametric down-conversion. BDP = beam-displacing prism. The second beam-displacing prism (BDP) in the signal path can be rotated about a vertical axis to generate interference fringes. PBS = polarizing beam splitter.

The 405-nm laser emits horizontally-polarized photons, so if the optic axis of the 405-nm half-wave plate is oriented vertically (0°) (or for that matter, horizontally (90°)), a pair of vertically-polarized 810 nm photons is generated. If the optic axis of the 405-nm half-wave plate is oriented at 45° so that the polarization of the incident laser is rotated to vertical, then a pair of horizontally polarized 810 nm photons is generated.

The birefringent quartz plate in Fig. 4-1 provides a means of zeroing the phase ϕ in the QM state for the entangled photon pairs:

$$\left|\psi_{DC}\right\rangle = a\left|H\right\rangle_s\left|H\right\rangle_i + b\exp(i\phi)\left|V\right\rangle_s\left|V\right\rangle_i \tag{4.1}$$

where normalization requires $|a|^2 + |b|^2 = 1$, and $|a|^2$ is the probability that the photon pair is polarized horizontally and $|b|^2$ is the probability of vertical polarization. The optic axis of the quartz plate is oriented vertically, so a horizontally polarized photon pair will experience a different refractive index than does a vertically polarized photon pair, and hence a phase difference is introduced between the two polarizations. Rotating the quartz plate about a vertical axis changes the effective thickness presented to the 405 nm beam, thus varying the phase difference imparted to the two polarization states. This is the method used to set $\phi = 0$ in Eqn. (4.1).

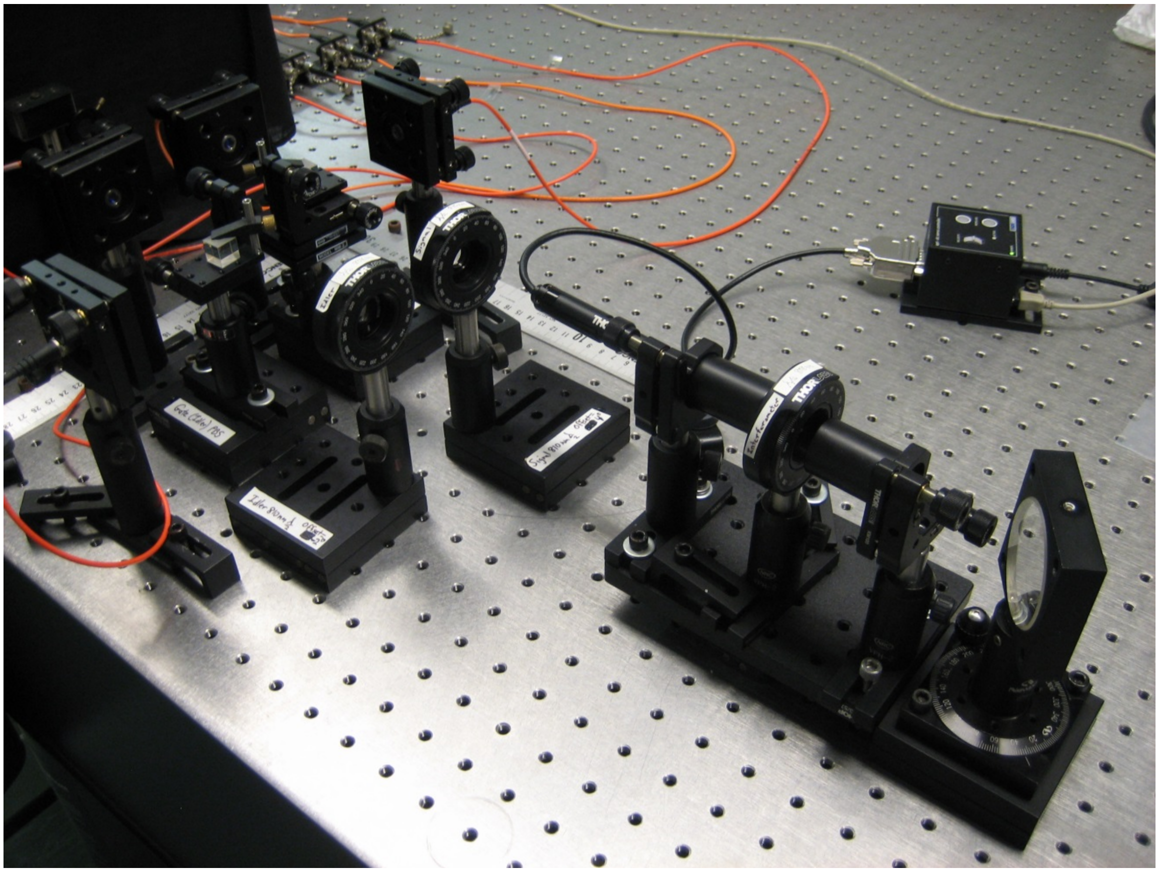

Fig. 4-2. Photo of the idler (left) and signal (right) paths. The idler path consists of the 810 nm half-wave plate and the polarizing beam splitter (PBS) followed by the G (transmission) and G' (reflection) fiber coupler/photodectors. The signal path consists of the glass plate, the polarization interferometer (beam displacing prism, 810 nm half-wave plate, beam displacing prism), 810 nm half-wave plate, and PBS followed by the T (transmission) and R (reflection) fiber couplers/photodetectors.

The polarization interferometer: Two beam-displacing prisms (BDP) and an 810 nm half-wave plate form a polarization interferometer in the signal photon path. The first BDP encountered by a signal photon deflects horizontally polarized photons (denoted with a double-arrowed line in the plane of Fig. 4-1) so that they emerge from the prism at a spatially separated position from the vertically polarized photons (solid dot in Fig. 4-1). Next the 810 nm half-wave plate, whose optic axis is oriented at 45° from the vertical, converts the horizontally polarized photons to vertically polarized photons, and converts vertically polarized photons to horizontally polarized photons. As a result, the second BDP brings the two polarized beams back together again. The beams are now colinear, but cannot interfere because they are orthogonally polarized. The second 810 nm half-wave plate, if oriented with its optic axis at 22.5° from the vertical, will rotate the polarization of both beams by 45°. The polarizing beam-splitter (PBS) in the signal photon path will now select the vertical (horizontal) components of both beams and allow them to interfere on the reflect (transmit) detector.

The glass plate in the signal photon path introduces a displacement of the photons that compensates for the displacement introduced by the polarization interferometer. The net zero displacement allows the polarizing beam splitter and detectors to remain in the same positions they would occupy if the experimental setup is used to explore the quantum nature of light or to test Bell's inequality.

Generating single photon interference fringes: If the polarization (horizontal vs. vertical) of the signal photon is unknown, even in principle, so that the signal photon takes both paths through the interferometer, then fringes can be generated by recording the coincidence count rate of the gate and transmit detectors (GT) as the second BDP is rotated about a vertical axis, thus changing slightly the path difference between the paths through the interferometer. Actually, the coincidence count rates GR or G'R or G'T could be recorded for the same purpose.

Which-way information and the quantum eraser: If the 810 nm half-wave plate in the idler photon path has its optic axis rotated to 22.5° from vertical, then an incoming diagonally (antidiagonally) polarized photon has its polarization rotated to vertical (horizontal) before it hits the polarizing beam splitter. Thus the detection of a photon by the gate-prime (G') or gate (G) detector indicates that the idler photon was originally diagonally or anti-diagonally polarized. This provides no information on the idler photon's polarization in the horizontal/vertical basis, and thus does not reveal whether the *signal* photon is horizontally or vertically polarized. Therefore, both both paths through the interferometer will be explored. For this orientation of the idler half-wave plate, fringes will be observed in the records of the GT or GR or G'T or G'R coincidence count rates as the second BDP in the signal path is rotated about a vertical axis.

However, if the 810 nm half-wave plate in the idler path has its optic axis oriented vertically (or horizontally), then a count in the gate detector indicates horizontal polarization of the idler AND signal photons, and fringes will not be recorded. Similarly a count in the gate-prime detector indicates vertical polarization of the idler AND signal photons, and fringes will not be recorded.

Therefore, simply rotating the idler 810 nm half-wave plate by 22.5° will cause the fringes to appear or disappear, even though the G and G'detectors might, in principle, be located very far from the T and R detectors. When the idler 810 nm half-wave plate is oriented vertically, the signal photon polarization provides which-way information and no fringes are observed. When the idler 810 nm half-wave page is rotated by 22.5°, the which-way information is “erased” and fringes are recovered – in the other arm of the setup! This is the spooky action-at-a-distance exhibited by quantum correlations in these entangled photon states.

For a beautiful and somewhat more detailed description of the apparatus and its behavior as a quantum eraser, see the paper (Gogo et al. 2005) by Mark Beck’s group at Whitman College (hardcopies are available in the 3-ring binders in the lab).

III Next Steps in Demonstrating a Quantum Eraser

Consult with your instructor to see where we are currently in acquiring data to demonstrate the complete removal of the single photon interference fringes. We suspect that a rotation of the 405 nm half-wave plate will change the relative numbers of horizontally and vertically polarized entangled photon pairs, and may make it possible to eliminate the fringes completely. We'll see! Other ideas and insights are welcome!!