Dickinson College Single-Photon Quantum Mechanics "Cheat Sheet"

The following document attempts to highlight the essential points for (a) using a blue laser to achieve spontaneous parametric down conversion (SPDC), (b) detect SPDC in a Grangier-type experiment, and (c) perform single-photon interference in a Mach-Zehnder interferometer. This document is not intended as a detailed step-by-step guide to the entire process, but instead to serve as a reminder of the important steps when aligning the experiments as we do at Dickinson College.

More details can be found in the upper-level laboratory manuals of Mark Beck (Whitman College) and Kiko Galvez (Colgate University). Note that our approach is more similar to Whitman's for the initial experiments (single-photon production and detection), but closer to Colgate's for the later experiments (single-photon interference and the quantum eraser).

Whitman Site and Lab Manual:

http://people.whitman.edu/~beckmk/QM/

http://people.whitman.edu/~beckmk/QM/Beck_QM_Manual.pdf

Colgate Site and Lab Manual:

http://departments.colgate.edu/physics/research/Photon/root/photon_quantum_mechanics.htm

http://departments.colgate.edu/physics/research/Photon/Photon%20research/Quantumlan07/Lab%20Manual2010.pdf

Blue Beam Alignment

1. Ensure the blue laser beam is level to the table and aligned along the rows of holes in the table by adjusting the two blue turning mirrors.
   a. Use a single iris to define the beam height. The iris can be pushed flush with two pairs of screws at different locations on table to set alignment to holes. (*See Galvez p. 13 for their description of this process.*) Do not adjust height of iris after completing this step.
   b. Insert and "dog-down" another iris far downstream and centered on blue beam. This iris defines the blue path in case you need to start over.
2. Insert the blue half-wave-plate (HWP) in the blue beam and "retro-reflect" the back reflection.
3. Insert the down-conversion crystal in the blue beam after the HWP and retro-reflect the back reflection.
4. Block blue beam for safety.

"A" Detector Alignment

1. Using a ruler on the table, measure a 3° cone angle and mount the A and B fiber-coupled detectors at the appropriate locations. Detectors should be mounted such that they can slide along a rail. (*See Beck p. 1-5 for details.*)

2. Use a fiber-coupled alignment laser (either He-Ne or integrated diode) to shine light back out of the A detector in order to "back-align" the A Detector to the crystal. (*See Beck p. 1-5 for details.*)

     a. Alignment beam must be level to the table and hit crystal at same spot as blue beam does. Use the original blue iris to define height of beam. You will need to adjust the vertical position of the fiber-coupled mount itself, as well as the vertical knob, to make the beam level to the table at the appropriate height. The A detector is now roughly aligned.

3. Turn off alignment laser and attach fiber from A detector to the single-photon counting module (SPCM). Open LabVIEW software, turn off room lights, and unblock blue beam. You should (hopefully!) see counts in the A channel above the background level. Our goal is to maximize these counts with the following adjustments:

     a. Tweak horizontal (H) and vertical (V) **knobs** on the A detector mount to increase A counts. Remember to avoid switching axes unless counts are at a maximum.

     b. Tweak blue HWP to increase A counts. Note final location of HWP.

     c. Adjust H-position of A mount (physically move the mount) along rail, iterating with the H-knob to increase A counts. (This is the hard part!)

     d. Tweak phase-matching angle of crystal to increase A counts.

     e. Insert 10 nm bandpass filter before A detector and repeat process until minimal improvement seen.

     f. Alignment of A detector is complete! Put in a pair of irises to define A beam path as follows:

          i. Block blue beam and turn off SPCM.

          ii. Use fiber-coupled alignment laser to shine light from A detector back toward crystal (do **not** adjust the A mount). Insert and center two irises (at different locations) on this beam. Make sure upstream iris does not interfere with the B beam path (it can block the blue if necessary).

"B" Detector Alignment

1. Alignment of B detector proceeds similarly to A detector (Step (3) above). The two key differences are:

    a. You should be **optimizing the AB coincidence counts** during each step (as opposed to the individual B counts). Although these typically move together, the phase-matching bandwidth of the crystal can be quite broad, and it is important that the B detector is seeing the same photon pairs that go to the A detector. (*See Beck p. 1-8 for details.*)

    b. Do **not** adjust the blue HWP or crystal until you have iterated through all the B detector adjustments a couple of times.

2. Once detector B is optimized, can tweak the blue beam steering (esp. vertical) **slightly** in order to optimize AB coincidence counts.

4. Alignment of the B detector is complete! As with the A detector, put in a pair of irises to define B beam path as did for A arm (Step (3f) above). Also make sure that the downstream iris is far enough away from B detector to allow insertion of waveplate and polarizing beam splitter in B arm.

5. You are now ready to observe the anticorrelation parameter between detectors A and B (see "Experiments" section). This should be quite high, since in theory the photons arriving at detectors A and B are perfectly correlated.

Beamsplitter and "B-prime" Detector Alignment

There are different approaches to this step, and we outline ours below. *See Beck p. 2-5 through 2-7 for an alternative approach.*

1. Using two separate mirrors, align the beam from a **polarized** He-Ne alignment laser to the irises that define the B beam path, noting the following details:
   a. Make sure the **B fiber is disconnected from the SPCM** before proceeding.
   b. The He-Ne is **not** fiber-coupled for this step.
   c. Since the second mirror needs to sit directly in the B beam path, the mount must be removable. There are various flip or magnetic mount options that can maintain their alignment when removed.
2. Once the He-Ne is aligned to the irises defining the B beam path, insert the polarizing beamsplitter (PBS) into the B arm near B detector. The PBS should be centered on the He-Ne beam and should be adjusted in order to retro-reflect the back reflection. Also make sure the reflected light from the PBS goes toward the B' location.
3. Insert red HWP upstream from the PBS. Again, center and retro-reflect the back reflection of the alignment laser. You may have to adjust the HWP rotation to send light toward B'.
4. With the **B' fiber disconnected from the SPCM**, insert B' detector to look at He-Ne light reflecting off of the PBS.
   a. Adjust V **knob** on B' detector to have detector lens roughly parallel to the table.
   b. Move V **position** of B' mount so that He-Ne light hits at the center of detector lens.
   c. Adjust H **position** and **rotation** of B' mount until you see He-Ne light coming out the free end of the fiber (this can be tricky).
   d. Once you find the light, carefully dog-down base and tighten post screw on B' mount.
   e. Tweak H and V **knobs** on B' detector to optimize He-Ne throughput.
5. Turn off He-Ne and remove its mirror in the B arm. Connect B' fiber to SPCM, turn off room lights, unblock blue laser, and look for counts. As with the B detector, you are looking to **optimize the AB' coincidence counts**. The optimization process is similar to the B detector, with the following two notes:
   a. Begin by adjusting the red HWP to send all the light to the B' detector.
   b. You can tweak the PBS during the process as well. (For small adjustments, the transmitted light through PBS undergoes negligible changes.)
6. Alignment of the B' detector is complete! You are now ready to measure the anticorrelation parameter for a variety of input states (see "Experiments" section). Be sure to rotate the red HWP to roughly equalize the number of AB and AB' coincidences.

Interferometer Alignment

We use a standard Mach-Zehnder (MZ) interferometer. Although this geometry is not optimal for mirror translation, we find that the obvious beam path separation and relatively easy alignment have pedagogical advantages. The two primary goals when aligning the interferometer are:

1. After recombination of the two beam paths, the output beams must be collinear to a very good approximation. As noted below, this is achieved by adjusting for a single interference fringe using a visible laser.
2. Since the bandwidth of the downcoverted light is quite broad, the path lengths must be equal to a very good approximation. As noted below, this is achieved by first aligning the two arms to the holes in the optical table and then using a white-light source to find zero relative time delay ("t=0").

We outline the essential steps of our procedure below. *See Galvez p. 11 through 16 for a more detailed description*.

1. We use the same He-Ne alignment laser path that we used for the B' detector. First, with the **B and B' fibers removed from the SPCM**, ensure that the He-Ne is aligned to the irises in the B arm. Second, insert another removable mirror that will send the beam to the interferometer.
2. Use this mirror to make sure the beam is both **level** (parallel to the surface of the optical table) and **aligned along the rows of holes** in the optical table. Do this using the original blue iris at two separated locations on the table. Be sure to push the iris base flush against screws in the same row of holes along the table. The greater the separation between iris positions, the better the precision. (*See Galvez p. 13 for their description of this process.*)
3. Insert a turning mirror before the first beamsplitter that changes the beam direction by 90$^\text{o}$. Once again, use the iris alignment procedure to ensure the beam coming off this mirror is both level to the table and parallel to the holes.
4. Insert the first beamsplitter (BS1). The beam should be centered on BS1. Using the iris alignment procedure, adjust BS1 so that the reflected beam stays level and travels parallel to the holes in the table. Note: depending on your implementation of the iris alignment procedure, this may involve iterating between moving the base of BS1 and adjusting the knobs on the BS1 mount.
5. Insert the two mirrors of the MZ interferometer. Once again, use the iris to have the reflected beams come off level to the table and parallel to the rows of holes. At least one of the mirrors will be on a translation stage – align the stage so that its axis of translation makes a 45$^\text{o}$ angle with the holes on the table. Note that since we are always making 90$^\text{o}$ turns, it is not necessary for the two mirrors to be exactly the same distance from BS1.
6. Insert the second beamsplitter (BS2). BS2 needs to be positioned such that the two beams intersect at the beam-splitting surface and exit BS2 collinearly. Using the iris alignment procedure, tweak the angle adjustments of BS2 to ensure that the reflected beam is level to the table and aligned along

the holes. This means that the reflected beam is now parallel to the transmitted beam, which was already aligned to the table in this manner. Now use the translation stage to change the overlap of the two beams at the beam-splitting surface. The beams should now be collinear exiting BS2.

7. Use a diverging lens to expand the output beams on a screen. You should see an interference pattern at this point. Adjust the knobs of BS2 to achieve a "single fringe" in the interference pattern. The interferometer is now aligned with roughly equal path lengths.

Interferometer Detector Alignment and Finding t=0

The procedure above produces a MZ interferometer with roughly equal path lengths. Since interference can only be seen for a path length difference less than the coherence length of the light, we need to ensure that the two paths in the interferometer are exactly the same (t=0). In addition, we need to align the fiber detectors to the interferometer output beams. We begin with the detector alignment:

1. With the **fiber disconnected from the SPCM**, insert one of the detectors to look at the He-Ne light from one output port of the interferometer. Align this detector to the output beam as detailed in Step (4) of the B' detector alignment procedure above. The detector should ideally be mounted along a rail so that it can slide transverse to the beam direction (like detectors A and B previously).
2. Repeat this process for the detector at the other output port (if desired).
3. Turn off the He-Ne and mount a white-light source (incandescent bulb) near the entrance mirror to interferometer. Connect the fiber from one of the output detectors to a visible wavelength range spectrometer (or off of a grating onto a card).
4. By adjusting only the position/orientation of the white-light source, look for a signal on the spectrometer. Do not adjust any portion of the interferometer.
5. If the interferometer is properly aligned, you should see modulations in the spectrum of white light, since some colors are interfering constructively and others destructively, depending on the exact path length difference. Only when the path length difference is exactly zero will all colors interference constructively (or destructively). By adjusting the translation stage position small amounts, you should see the modulation pattern in the spectrum change. Move the stage until all the colors interfere in the same manner ("single white-light fringe"). The path length difference is now essentially zero. (*See Galvez p. 15 for a figure.*)
6. Finally we need to optimize the down-conversion coincidence counts between detector A and the two detectors at the output of the MZ interferometer (which we again call B and B'). Remove the white-light source, connect the fibers to the SPCM, turn off the room lights, unblock the blue laser, and look for counts. As before, you are looking to **optimize the AB and AB' coincidence counts**. The optimization process is similar to the earlier detectors, with the following two notes:
   a. It is very helpful to block one arm of the interferometer with a card so that you are not sensitive to the noise due to optical interference.
   b. Adjustments should be made primarily to the new B and B' detectors (only adjust A and the blue HWP / crystal at the end).
   c. Remember to use the 10 nm bandpass filters for final optimization.
7. The interferometer is now aligned. You are ready to perform the single-photon interference and quantum eraser experiments.

The Experiments

The descriptions below highlight the main experiments we do at Dickinson College.

1. **Anticorrelation Parameter for Incandescent Light Bulb**

   Light Source: Incandescent bulb placed just after down-conversion crystal.

   Filters: **ND filters immediately after bulb**.

   Detectors: B and B'.

   Software: LabVIEW Down Conversion Coincidence, g(2) 2-det. on BB'.

   Result: Two-detector g(2) = 1.

2. **Anticorrelation Parameter for Laser Light**

   Light Source: He-Ne laser aimed into B-B' arm.

   Filters: **ND filters immediately after laser**.

   Detectors: B and B'.

   Software: LabVIEW Down Conversion Coincidence, g(2) 2-det. on BB'.

   Result: Two-detector g(2) = 1.

3. **Two-Detector Anticorrelation Parameter for A and B Arms of Down-Converted Light**

   Light Source: SPDC into A and B arms.

   Filters: 10 nm bandpass filters before red HWP in both A and B arms.

   Detectors: A and B. (Note need to switch cables for A and B' for software.)

   Software: LabVIEW Down Conversion Coincidence, g(2) 2-det. on BB' (which is really BA).

   Result: Two-detector g(2) in the hundreds.

4. **Two-Detector Anticorrelation Parameter for Single-Arm of Down-Converted Light**

   Light Source: SPDC into B-B' arm.

   Filters: 10 nm bandpass filter before red HWP in B-B' arm.

   Detectors: B and B'.

   Software: LabVIEW Down Conversion Coincidence, g(2) 2-det. on BB'.

Result: Two-detector g(2) = 1.

5. **Three-Detector Anticorrelation Parameter for Down-Converted Light (Grangier)**

   Light Source: SPDC into A and B-B' arms.

   Filters: 10 nm bandpass filters before red HWP in both A and B-B' arms.

   Detectors: A, B, and B'.

   Software: LabVIEW Down Conversion Coincidence, g(2) 3-det. on ABB'.

   Result: Three-detector g(2) approximately equal to 0.

6. **White-Light Interference**

   Light Source: Incandescent bulb placed just before entrance mirror to MZ interferometer.

   Filters: None.

   Detectors: B after MZ interferometer **going to RedTide Spectrometer** (do **not** let into SPCM).

   Software: LoggerPro "whitelight_fringes.cmbl" template (spectrometer viewing software).

   Result: Single white-light fringe when at t=0.

7. **Single-Photon Interference and Quantum Eraser**

   Light Source: SPDC into A arm and B detector at output of MZ interferometer.

   Filters: 10 nm bandpass filters before red HWP in A arm and before MZ interferometer.

   Detectors: A and B after MZ interferometer.

   Software: APT User (control for stage in MZ interferometer). LabVIEW Down Conversion Coincidence. Monitor AB coincidence rate in LabVIEW as translate stage.

   Result: Interference in AB coincidence rate as stage moves when polarizations parallel ("untagged"). No interference when polarizations perpendicular ("tagged"). Interference returns when polarizer placed after MZ interferometer ("erased"). Also note can get rid of interference by moving stage past coherence length of light with all filters removed. Interference will return when narrow-band filter placed in A arm only.