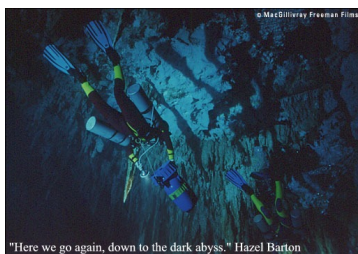


In the dark abyss: No photon magic.



What to do?

(Kiko Galvez 6/2015, Revised 6/2016)

1- Really stuck: No coincidences. Make sure that the crystal is properly aligned. You do this by tilting the crystal. The counts of both singles (individual detectors) should rise sharply as a function of the tilt of the crystal, and together go down as you keep tilting. **If they do, go to #2. If not, then there are three options:**

- a. **Neither channel rises sharply at some tilt angle.** There are two possibilities.
 - i. **If there are no counts above background** (a few hundred counts/s) in either detector, you are in a dark place! You must set the collimators at the proper positions, forming equal angle with the pump and at the same height. See procedures we have posted to do this. Currently, our best technique uses a set of Thorlabs components (Fig. 1a): mount fiber collimators (F220FCB) onto an adapter (AD11F) that is 1 inch in diameter with a threaded edge. The collimator+adapter are screwed onto a 1-inch mirror mount with threaded opening (KM100T), but not all the way: leaving a few threads out. Then screw an iris with inner threads (SM1D12) to the free threads of the adapter. The assembled parts are shown in Fig. 1b.

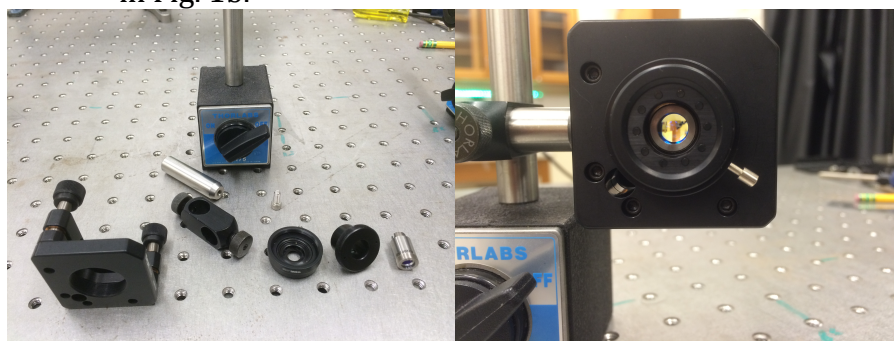


Figure 1 (a) Left frame has components. From left to right (front): Mirror mount (KM100T), post holder (RA90), threaded iris (SM1D12), adapter (AD11F), collimator (F220FCB); (back) ½-inch post (TR3) and magnetic base (MB175). (b) Right frame has assembled collimator.

Two more components are used: A 1-inch diameter, 1/8-inch (thin) mirror mounted on a lens tube mount (SM1L05), which threads into the iris. This is for aligning the tilt of the collimator. The other component is the 1-inch diameter band-pass filter (FB800-40) on a similar lens tube mount. Once the collimator is aligned, we screw-in the filter.

- ii. **If there are a lot of counts**, the problem is that the crystal is at the wrong orientation and some other IR is getting to the detector: Some blue lasers have a strong IR component that could be scattered by the crystal; or some piece of optics (filter etc.) that is in the path of the blue laser is fluorescing, and you are getting that fluorescence; or the pump somehow found a way to your detectors through some odd reflection. You can solve this by tilting the crystal. This normally gets rid of this. Otherwise you need to put a filter that passes the pump and blocks the IR. You can also use cross polarizers before and after the crystal (down-converted photons are perpendicular to the pump), but this should be a temporary solution, because the polarizer after the crystal could wedge the down-converted photons or the polarizer before could also produce IR fluorescence.
- b. **If one channel rises sharply but not the other**, that is suspicious. Your other collimator could be way off in alignment, or the optical fibers are not being hooked-up correctly. The crystal may well be in the wrong spot: both detectors have to have a sharp dependence with the tilt of the crystal.
- c. **If both detectors show a sharp peak with the tilt angle of the crystal but they do not peak at the same angle**, then in this case the two collimators/detectors are not at the same angle relative to the pump beam. Fix: Tilt the crystal until ch1 is a maximum. Then displace collimator 2 along a curved path centered about the crystal until it peaks. Then repeat the tilting until you see that both peak at the same tilt angle. We make a plate that has a 1-m radius of curvature and place the collimator mount against it, as shown in Fig. 2. When we slide the collimator mount with the plate as a guide, the collimator changes position while still looking at the crystal. If you have a straight-plate guide that can also work, but if you go too far the collimator will get out of alignment.

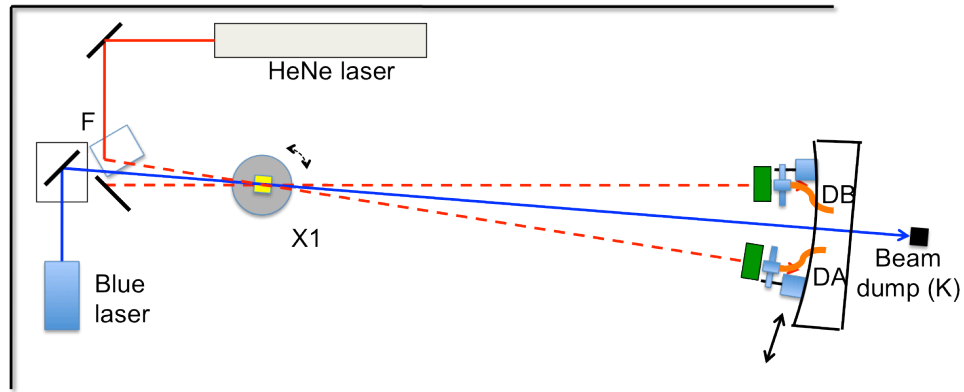


Figure 2. Schematic of the alignment of the collimators using a 1-m radius-of-curvature plate.

- 2- **If both detectors peak with the tilt but the coincidences are low**, then you are detecting coincidences but not the partners. There are two possibilities:
- There are three "beams" of photons in this problem: the pump, and the two down-converted photons. All three have to be in the same horizontal plane (see below). If they are not, then you can get high single counts but no partners. The fix is to realign the paths and make sure all three are at the same height. We do this with an auxiliary visible laser beam.
- An alternative is to tilt the pump beam vertically, to put it in the same plane as the down-converted photons.

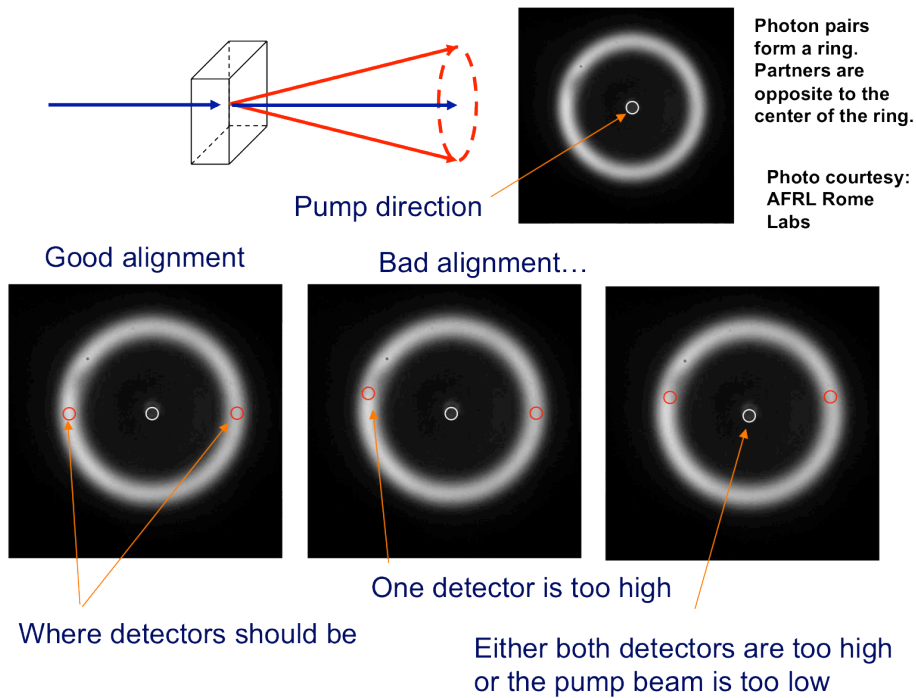


Figure 3. Potential problems due to mis-positioned collimators.

- b. We use narrow band-pass filters (1, 10, 25, 40 nm). It is possible that the filters are missing the partners. Measure the wavelength of the pump. The filters should be within twice the wavelength of the pump. Some blue diode lasers can be way off the nominal value (405 nm). If a diode is say at 408 nm and the filters are set to 810 +/- 5, the filters are just missing the partners. The filters will still get other down-converted photons: 810 nm but with partners at 822 nm, which is blocked by the filter.
- 3- **If coincidences are good but the entangled state is not “good.”** This is the important step for when you want to perform a violation of Bell’s inequalities. The idea is that the entangled state HH+VV (unnormalized) transforms into DD+AA (note that signs are very important). If there is a non-2-pi phase between HH and VV, then in the diagonal basis you do not get DD+AA. If for example you have HH-VV, then in the diagonal basis you have DA+AD. So the test for a good entangled state with HH+VV is to orient the polarizers to DA (or AD) and tune the phase for a minimum (a really good one, 2% or less than maximum). For tuning this you have a half-wave plate (HWP) followed by a quartz plate (QP), of 5-7 mm in thickness with fast axis parallel to the face of the plate (so called “a-cut”), before the BBO crystal pair (we assume you know about this). This is shown in Fig. 4.

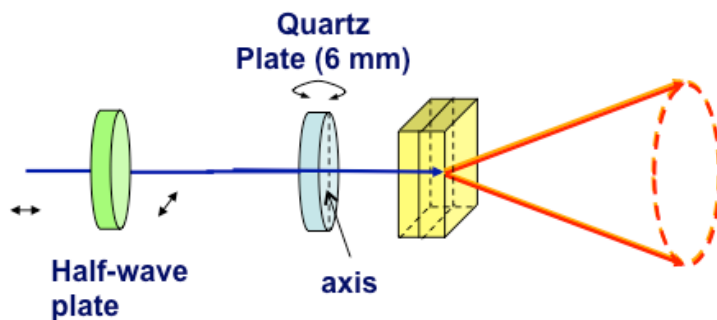


Figure 4. Schematic of the setup to make entangled states.

If the coincidences are not near zero, you do not have a good entangled state. There could be several reasons for this:

- a. **The coincidences for HH and VV are not the same.** The coincidences for HH and VV have to be the same. They may be different due to distinct efficiencies in the production of the two states. You solve this by rotating the HWP while looking at the HH and VV coincidences, and adjusting them to be equal. The HWP controls the amount of H and V components of the pump that are incident on the crystals. Adjusting their ratio pre-compensates the unequal efficiencies in producing HH and VV.
- b. **The coincidences are 20% or higher when tuning the QP.** Even if HH and VV coincidences are the same you may not get the DA coincidences to be near zero (of the order of accidentals). First, to minimize, you have to

turn the QP slightly (degree or fraction) and adjust the DA coincidences to a minimum by varying this tilt. If your minimum is 20% or higher of the maximum, then you have a partially mixed state. It will not produce a violation of Bell inequalities. That is, the HH and VV states are partially distinguishable. If the crystals are thin (0.5 mm or less each) and the down-conversion angle is low (few degrees), then the problem may be that HH and VV are temporally distinguishable. The QP inserts a phase between HH and VV with tilt, but it also delays one vs. the other. Even without QP the pairs leave the crystals at different times. This is because for one case the pump travels through say the first crystal at a certain speed to produce pairs in the second crystal, and in the other case the pump creates the pairs in the first crystal and the pairs travel through the second crystal. When the crystals are BBO 0.5 mm thick, this difference in time is about 207 fs or about 60 μm travel difference in free space. If the bandwidth of the pairs is 40 nm (due to filters), their wave-packet length is 16 μm . For 10-nm bandwidth this is 66 μm . Thus, without temporal compensation, they barely overlap. We need to delay one pair relative to the other with the QP. Our calculation gives 6.4 mm thickness to be the optimal to delay the two possibilities (You can see this calculation in the file `bbocompensationpql.pdf`). That is, if the QP is oriented correctly. If it is oriented orthogonally to the correct orientation, it will *double* the time between HH and VV, and make matters worse. So if the QP is not producing a minimum, it means it is in the incorrect orientation, so rotate the plate by 90 degrees (about the axis perpendicular to the plate).

4- Coincidences are good but there are no interference fringes in single-photon interference.

- a. **The Piezo.** An easy problem to have is that the piezo-electric is not changing its length. You test this by looking at the interference with a HeNe laser and seeing it change as the voltage on the piezo is changed. Often piezos stop working, so it is good to have a couple of spares. Replacing it may involve a realignment.
- b. **Alignment.** This is the most common but challenging problem to have. The photon bandwidth determines the coherence length L_c . The bandwidth of the down-converted photons is determined by the bandpass filters in front of the collimators. A bandwidth of 40 nm is our top choice of filters because they are easily available commercially and can still produce very good results. This gives $L_c = \lambda^2 / \Delta\lambda = 16 \mu\text{m}$. The problem is that to see interference the difference in path length has to be smaller than the coherence length. If you do not see interference, it means that the difference in length of the two arms of the interferometer is a few times the coherence length. The Mach-Zehnder interferometer must be aligned with a HeNe laser. In other documents we show how to align the laser beam with the rows of holes on the breadboard. The input laser beam has to be aligned parallel to the rows of holes, and each component has to be aligned to steer the beam 90-degrees, done also by aligning the

corresponding reflections using the same method. This step is critical. If you say to yourself “good enough,” it is probably not so. Possible bad alignments are shown in Fig. 5.

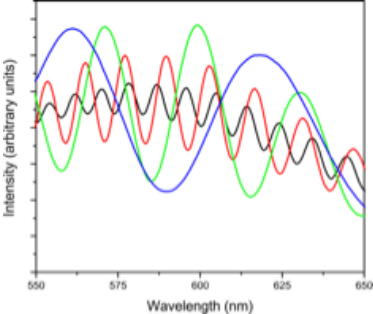


Figure 5. Potential alignment problems: (left) one of the components does not steer the beam by 90-degrees; (right) the input beam is not aligned with the breadboard. Both cases will be enough to preclude observing interference.

Once this alignment is done you are not there yet: most careful alignments get you an arm-length-difference of probably 50-100 μm . By this point the interferometer is aligned so that the two beams overlap and as you gently touch the base of one of the elements of the interferometer you see the beam get all bright or all dark. If your best alignment gives you a beam with a dark spot in it, then the alignment is not good enough, and you have to start all over.

The next step is to send white light through the interferometer (a small light bulb) and observe it with a fiber spectrometer (we use Ocean Optics), with the light-collecting fiber as close to the interferometer output as possible without touching its components. You should see fringes in the spectrum. If you do not, you can fish around by turning the micrometer that pushes the translation stage that mounts one of the mirrors. If the fringes do not appear after a few nudges of the micrometer in either direction, you are doomed: you have to realign. Patience is very important. You cannot be rushed. If you are frustrated, take a break and return later. These words come from experience...

If the white light fringes are there, you are golden. Adjust the micrometer to make them as broad as you can. Figure 6 shows what you get as you turn the micrometer. Once you are done, you have still one last step. Make sure that the HeNe fringes are as broad as possible.



$$\Delta L = \frac{\lambda^2}{\Delta\lambda}$$

| Color | $\Delta\lambda$ (nm) | ΔL (μm) |
|-------|----------------------|------------------------------|
| Black | 8.6 | 38 |
| Red | 12 | 27 |
| Green | 28 | 12 |
| Blue | 55 | 6 |

Figure 6. White-light fringes in a spectrum for different path-length differences.