Single Photon Interference

1. References

[1] E.J. Galvez et. al. "Interference with Correlated photons: Five quantum mechanics experiments for undergraduates", Am. J. Phys. **73**, 127-140 (2005).

[2] A.C. Melissinos, J. Napolitano. *Experiments in Modern Physics 2nd Ed.* Academic Press (2003).

!! DANGER !!

The pump laser beam WILL cause permanent damage, possibly blindness, if it strikes your eye. Wait for instructions before turning on the pump laser.

Laser safety goggles MUST be worn at all times when the laser is on, even when the table is covered.

2. INTRODUCTION.

In this experiment you will investigate the behavior of individual photons passing through an interferometer. This system will yield surprising, anti-intuitive results. These results focus attention on some unique aspects of quantum mechanics such as the behavior of photons, distinguishability of paths, and the effects of observation on experimental outcomes.

Classically we treat light as a continuous electromagnetic wave. When such a wave enters an interferometer it is split into two waves, each taking a different path before the two waves are recombined (interfere).

Quantum mechanically, light is treated as being composed of indivisible *photons*. For high intensities, light could be considered a "continuous" beam of photons. However, as we shall see, the classical description of interference fails with the photon model.

Consider the case of sending one photon at a time through an interferometer. If the photon is indivisible, then it must take either one path or the other through the interferometer, but not both. Thus, it would seem that no interference would result for the case of a single photon. However, quantum mechanics predicts that under certain circumstances single photons will indeed interfere with themselves.

3. THEORY. Work in progress. See external sources.

4. APPARATUS

Figure 5 shows the layout of the components on the optical table. Functionally, the components can be listed in four parts:

- The correlated photon source.
- The Mach-Zehnder interferometer.
- A HeNe laser for aligning and calibrating the interferometer.
- Mirrors for directing light into the interferometer.

Positioning and alignment of the various components must be done with great precision. Due to time constraints, the optical components have been aligned on the table for you. You will perform some manipulations during the experiment.

IMPORTANT

Changing the alignment of any optical component could result in a full day's delay. When working on the optical table.

- Think about where you are putting your hands.
- When operating the flip mirrors do not contact the thumb screws which adjust the orientation of the mirror. Do not touch the optical surfaces.
- When rotating the half-wave plates, do not twist the filter holder in the post holder. The face of the wave plate must remain normal to incident light.

4.1 BBO Crystal.

Our source of correlated photon pairs is a Beta-Barium-Borate (BBO) crystal. Deformations of bonds in such a crystal respond non-linearly to incident light *(pump photons)*, and therefore produce outgoing light with different frequencies from the incident light. This process is called *spontaneous parametric down conversion*. The incident pump photon is converted into a pair of photons called *type-I parametric Down Converted* (DC) photons. If the pump photons are incident on the BBO crystal at the correct angle, with respect to the optic axis of the crystal, the DC photons will each have half the energy of the pump photon and will be emitted with a well defined opening angle θ as shown in figure 1.

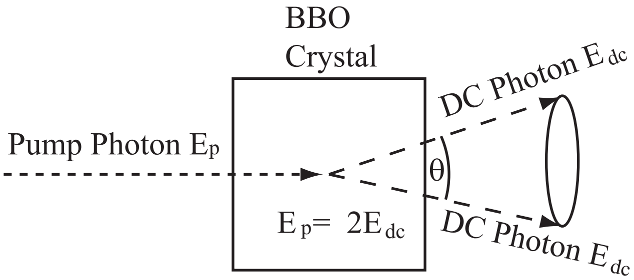


Figure 1. Photon down conversion in BBO crystal.

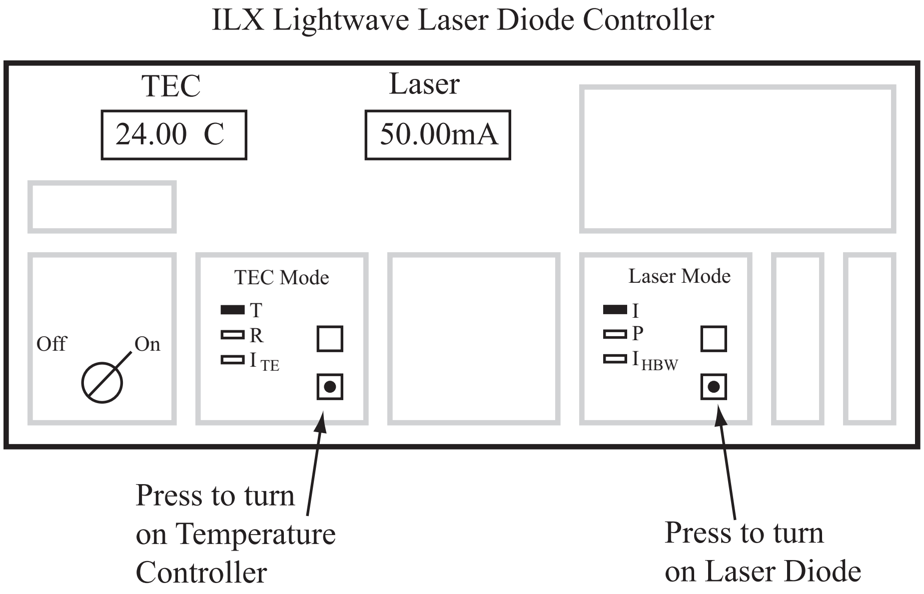
The DC process is symmetric about the axis defined by the pump photon trajectory. Thus, DC photons leave the crystal with trajectories lying on a cone with opening angle θ. Type-I parametric down conversion for our BBO crystal requires that the pump photons be linearly polarized in the horizontal plane. The DC photons are produced with vertical polarizations. The angle of the BBO crystal face, with respect to the incident pump beam, has to be set precisely in order to produce DC photons. Take care not to disturb the BBO crystal or any of the optics which direct the pump beam onto the crystal. For a more detailed description of the DC process see Ref. [1].

By convention, one of the DC photons in a pair is designated as the *idler* photon, the other is the *signal* photon. In our experiment we will refer to the photon which enters the interferometer as the signal, and the other half of the pair as the idler.

4.2 405 nm Pump Laser.

Our source of pump photons is a 20 mW, 405 nm diode laser. The collimated beam from this laser reflects off of two aluminum coated mirrors and is directed onto the BBO crystal. In order to rotate its plane of polarization into the horizontal plane, the pump laser beam first passes through a half-wave plate before entering the crystal. The requirement that the DC photons each have half the energy of the incident pump photon leads to DC photon wavelengths of 810 nm.

The pump laser diode is controlled by the ILX Lightwave laser diode controller (Fig. 2). The controller has two functions, it maintains the diode at a constant temperature (TEC Mode) and it controls the current which operates the laser (Laser Mode). Both the operating temperature (24ºC) and current (50mA) have been preset.



Press to turn on Temperature Controller

Press to turn on Laser Diode

Figure 2. Laser diode controller.

4.3 Avalanche PhotoDiodes.

The photon detectors we use are Avalanche PhotoDiodes (APDs). Ordinary photodiodes are semiconductor devices which generate an electric current when illuminated by visible light. Photons liberate electrons in the semiconductor via the photoelectric effect. The magnitude of the current is proportional to the intensity of the light striking the diode. These detectors are not suitable for detecting single photons however because the flow of current would be too small. APDs operate analogously to a photomultliplier tube in that they use an avalanche process to produce a large number of liberated electrons for each photon captured.

The APD modules we use are designed for single photon counting and produce a TTL output pulse for each photon detected. APD's can be damaged if directly exposed to too much light, such as room lights. Our APDs are protected from the room lights by coupling them to a fiber optic cable with a collimating lens which only allows photons coming straight into the lens to reach the APD. Further, we place a narrow bandpass interference filter in front of the fiber optic collimating lens which passes only photons with wavelength 808nm ±5nm. The bandpass data for the filters is posted in the lab.

Power to the APDs should never be turned on if the APDs are not connected to the fiber optic cables and with the narrow bandpass filters in place. Check that this is the case before turning on the APDs.

In this experiment the DC photons produced in the crystal propagate outward along the surface of a cone as described earlier. One of the APDs (labeled APD#1) is positioned to detect DC idler photons directly. Two other APDs (APD#2 and APD#3) are positioned to detect DC signal photons emerging from the two outputs of the Mach-Zehnder interferometer.

4.4 Mach-Zehnder Interferometer.

A Mach-Zehnder interferometer consists of 2 50/50 beam splitters and two mirrors as shown in Fig. 3.

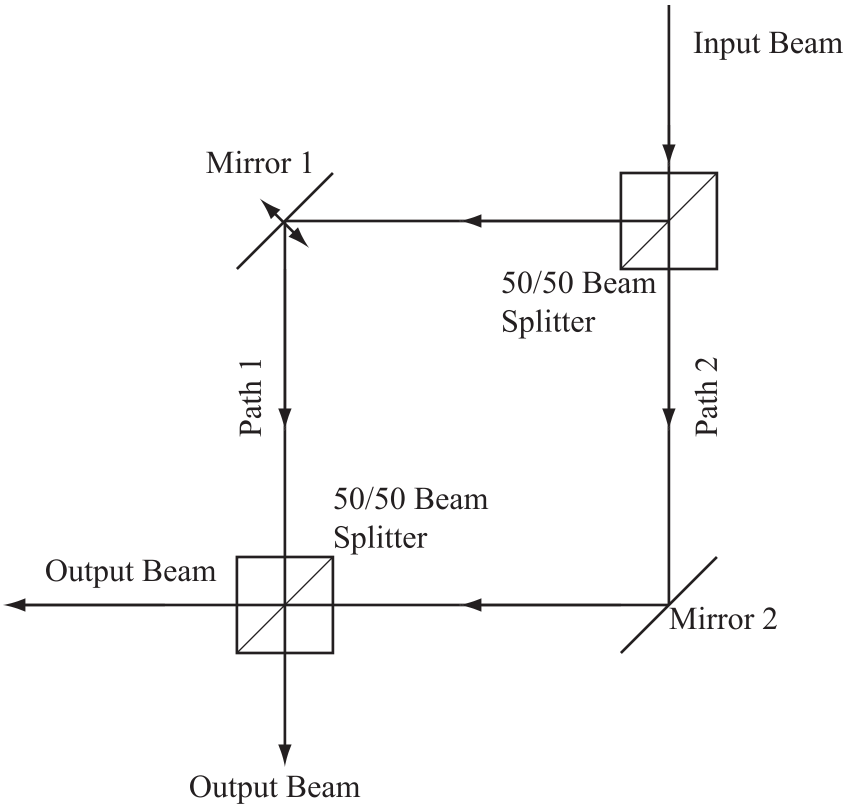


Figure 3. Mach-Zehnder interferometer.

Light entering the interferometer is split at the first beam splitter, half the intensity travels Path1 and half travels Path 2. After reflecting from a mirror, light from each path recombines at the second beam splitter. If the light is monochromatic and the length of Path 1 and Path 2 are different there will be a phase difference between the two beams when they recombine at the second beam splitter. If one of the mirrors is displaced, the path length difference between Paths 1 and 2 changes. Thus, there is a change in the interference condition at the output. Notice that there are two output beams, each with half of the intensity of the input beam, in this type of interferometer.

The details of our Mach-Zehnder interferometer are shown in Fig. 5. DC photons from the BBO crystal are reflected into the interferometer by *Flip Mirror 2*. A *linear polarizer*, with its pass axis aligned vertically, is placed after *Flip Mirror 2* to reduce the amount of unwanted background light entering the interferometer (recall that the DC photons are vertically polarized). The DC photons then strike a *50/50 Cube Beam Splitter* on which each photon has a 50% chance of being reflected or transmitted. After leaving the *50/50 Cube Beam Splitter*, photons on either path pass through a *½ Wave Plate* before reflecting off of a mirror and entering the second *50/50 Cube Beam Splitter*.

A waveplate (*or retardation plate*) is a material with two orthogonal optical axies, called the fast and slow axies. The waveplate has different indicies of refraction along these two axies such that light whose polarization is parallel to the fast axis propagates through the material faster than light whose polarization is parallel to the slow axis. When the polarization of the light lies between the fast and slow axies of the wave plate, the components of the light which project onto the fast and slow axes will propagate at different speeds and will emerge from the wave plate with some phase difference. A ½ wave plate has been designed so that for a specific wavelength of light the components along the two axies will be out of phase by one half a wavelength after passing through the waveplate. As a result, depending on the relative orientation of the ½ wave plate axes and the polarization of the incident light, the polarization of the light leaving the ½ wave plate can be rotated.

We will use the ½ wave plates to manipulate the degree of distinguishability of the two paths through the interferometer. When the ½ wave plate filter holders are rotated to read 0° the slow axis of the wave plate will be vertical. Since the DC photons are vertically polarized their polarization will not be rotated, and the two paths through the interferometer are indistinguishable. When one of the wave plates is rotated by 45°, the polarization of photons passing through them will be rotated by 90° into the horizontal plane. If the other wave plate is left at the 0° mark we have a configuration where photons traveling through one arm of the interferometer are horizontally polarized and photons traveling the other arm are vertically polarized. The two paths can now be distinguished by measuring the polarization of the photon after passing through the interferometer.

One of the corner mirrors is mounted to a *Piezoelectric crystal*. A *Piezoelectric crystal* (piezo) has the property that it expands when a voltage is applied to it. This expansion is highly repeatable and can be controlled at the level of fractions of a micron. By applying a voltage to the piezo we can displace the attached mirror, and hence change the path length of this arm of the interferometer, by a fraction of the wavelength of a DC photon. The piezo voltage is controlled by the y-axis of the *3 Axis Piezo Controller* in the electronics rack (Fig. 4).

The other corner mirror is mounted on a *Micrometer Stage* which allows the length of the two arms of the interferometer to be precisely matched. The *Micrometer Stage* has already been adjusted so that when the piezo voltage on the opposite mirror mount is set to 50V, both arms of the interferometer are the same length.

Photons leaving the second *Beam Splitter* are detected by APD#2 or APD#3 depending on which output path they took. In front of APD#2 is a post holder which can hold either a *Linear Polarizer* or an *Empty Filter Holder*. The linear polarizer is used for the quantum eraser part of the experiment. Otherwise an empty filter holder should be placed here so that the effective aperture of the APD remains constant for all measurements.

4.5 HeNe Laser and ThorLabs Photodiode.

The HeNe laser, wavelength 632.8nm, is used by the lab staff to align the optical components of the interferometer, and by the student to calibrate the path length change as a function of the piezo voltage. To turn the HeNe laser on simply plug I its power supply.

When making measurements of DC photons Flip Mirrors #1 and #3 should be in the down position and #2 in the up position. If the HeNe is on during such measurements, which may be necessary to allow the laser to warm up to a stable output intensity, its beam should be blocked using a piece of black foam board.

To use the HeNe beam to calibrate the piezo, place Flip Mirrors #1 and #3 in their upright position and #2 in the down position (See Fig. 5).

Take care not to change the orientation of the mirrors when raising and lowering them.

The beam from the HeNe will now pass through the interferometer and onto the face of the ThorLabs photodiode. Connect the output of the ThorLabs photodiode to the scope. The voltage measured on the scope is proportional to the intensity of the light striking the photodiode. The full beam from the HeNe is bright enough to saturate the photodiode. Saturation is evident when the photodiode voltage remains fixed at 15V as the piezo voltage is varied. By placing a variable neutral density filter in front of the photodiode you can reduce the intensity of the HeNe beam below the saturation level. The signal should be about 10V and should vary as the piezo voltage is adjusted.

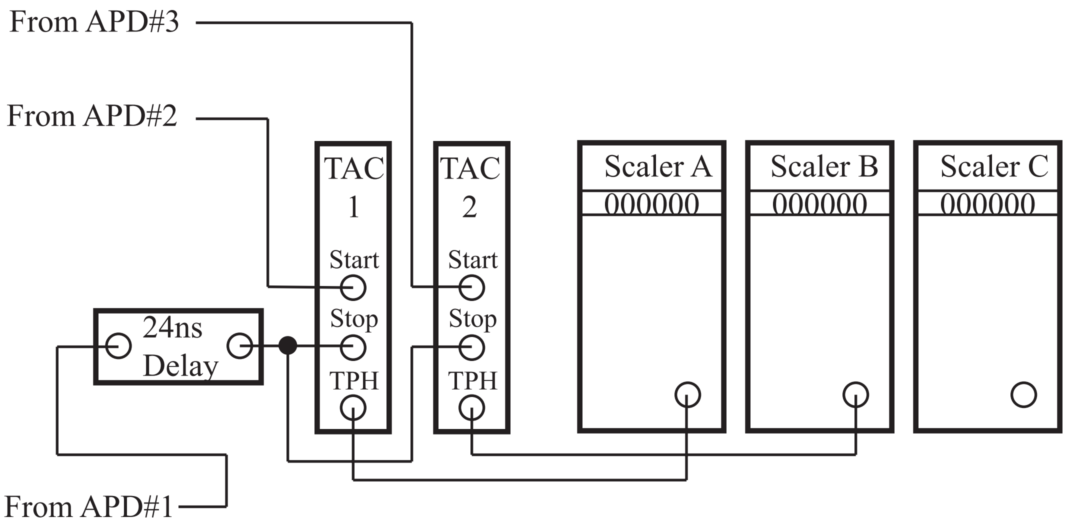


Fig. 4 Nim electronics set for #1#2 and #1#3 coincidences

5. PROCEDURE.

Turn on the ILX Laser Diode Controller using the key switch on the lower left corner of the operating panel and then press the button indicated by the GREEN dot in the *TEC Mode* section of the control panel. The temperature of the diode is indicated by the TEC LED display and should reach 24ºC in a few minutes.

When it is time to turn on the pump laser, press the button indicated by the *Orange* dot on the *Laser Mode* section of the control panel. The diode current, as indicated on the LED display, should read 50 mA when the laser is on.

5.1 Background Noise Rates.

APDs, like photomultiplier tubes, will produce some pulses even in the absence of light (*dark rate*). Another source of background is stray room light. Ideally we would like rate of detected DC photons to be significantly greater than the background or noise rate.

There is also a maximum rate of pulses above which it is possible to damage the detectors ($$!). Although the APD modules are internally protected from excessive count rates, one should not approach the maximum allowable count rates.

If you ever measure APD count rates over 1MHz immediately turn the detectors off and get the TA or lab staff to assist you in determining the cause of the excessive rates.

Connect the output of each APD to a scaler in the NIM bin (Fig. 4).

Turn on the APDs and measure the count rate (singles rate) from each of the detectors, under the following conditions:

- With the room lights *off* and the table *covered*.
- With the room lights *off* and the table *uncovered*.
- With the room lights *on* and the table *covered*.
- With the room lights *on* and the table *uncovered*.

From the data sheets for the detectors you can obtain the expected dark rates for the APDs.

Q: *How do the measured count rates for the different room lighting conditions compare with the expected dark rates?*

Cover the table and turn on the 405 nm pump laser to produce a flux of DC photons from the BBO crystal. Measure the APD count rates.

Q: *How statistically significant are the noise rates in comparison with the DC rates?*

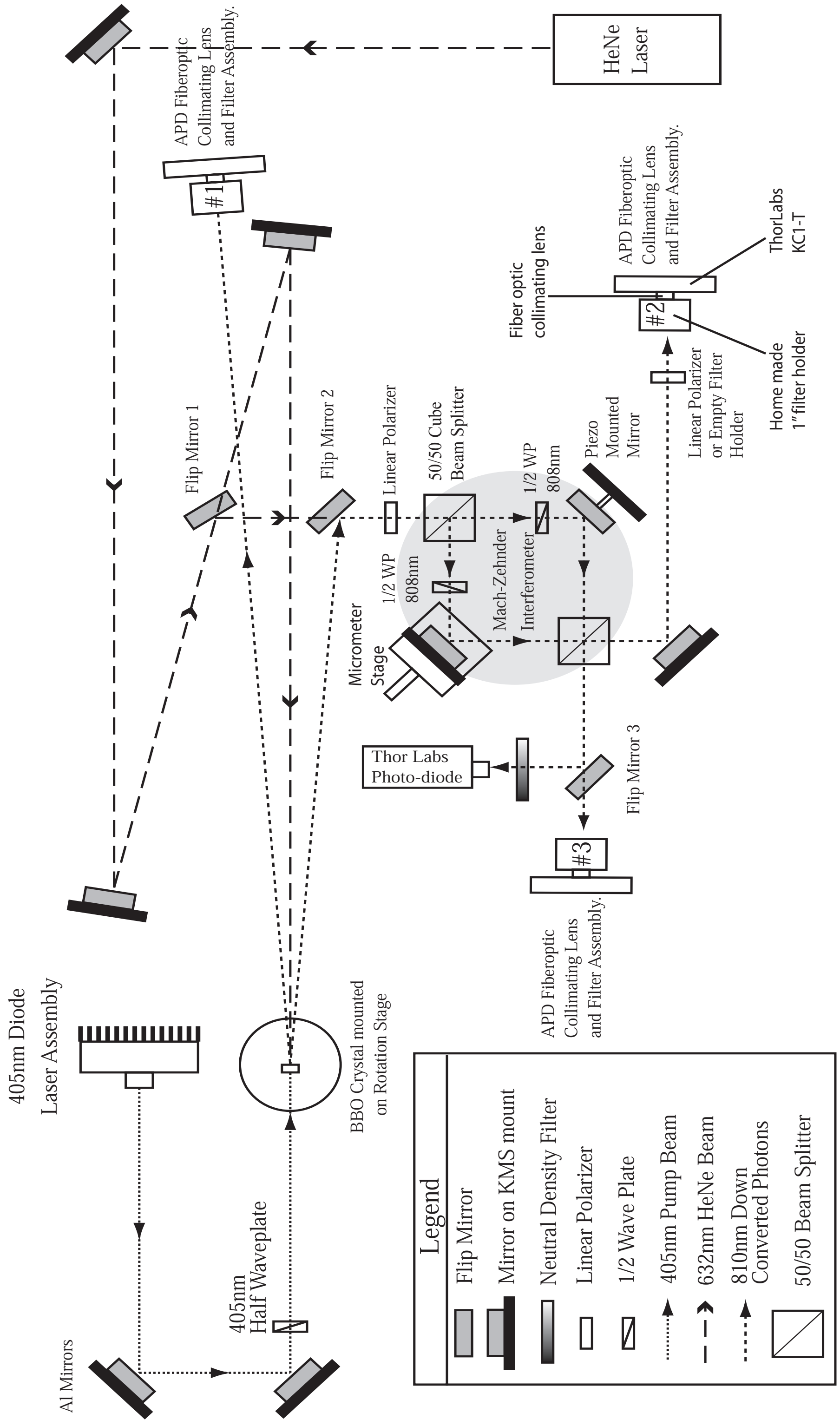


Figure 5. Beam paths and layout of components on the optical breadboard.

5.2 Coincidence counting.

Verify that the components on the optical table are laid out as shown in Fig. 5.

All APDs should have their 10 nm bandpass filters in place. In order to send the DC photons to the interferometer, flip mirrors #1 and #3 should be in the down position and #2 should be up. To make the two paths of the interferometer indistinguishable, both half-wave plates should be rotated to the 0° mark. The piezo voltage should be set to 50V.

To set up for counting coincidences verify that signals from APDs#2 and #3 arrive at the same time as the signal from APD#i. To do so, connect APD#1 to the external input of the scope and connect APD#2 and APD#3 to channels 1 and 2 of the scope. Set the scope to trigger externally (on APD#1). *What is the width, in seconds, of the APD pulses?* Set the scope display to infinite persistence. You should see a significant number of pulses from APD #2 and APD#3 that arrive at the trigger point (therefore, in time with a pulse from APD#1). Do they?

Connect the electronics as shown in Fig. 4 to monitor coincidences between APD#1 and APD#2 (hereafter referred to as #1#2 coincidences), and APD#1 and APD#3 (hereafter referred to as #1#3 coincidences). Use the scope to confirm that the pulse entering the TAC *Stop* input arrives about 24 ns after the *Start* pulse. Both TACs should have their time range set to 50ns.

5.3 Accidental Coincidence Rates

All measurements should be made with the incandescent lights off, since they contain a large intensity in the infra-red.

Pump laser off, fluorescent room lights on and table covered

Measure the #1#2 and #1#3 coincidence rates. With the laser off you are measuring accidental coincidences due to un--correlated photons which just happen to arrive at the detectors within 50ns of each other. Count for a long enough time to accumulate a statistically significant number of accidental coincidences.

Measure the “singles” count rates for all three APDs by connecting them directly to scalers. under the same conditions as you just measured the coincidence rates. For a discussion of calculating the expected rate of accidental coincidences see ref [2] p412.

Q: *From the singles rates and the pulse widths calculate the expected number of accidental coincidences for #1#2 and #1#3. Are the measured coincidence rates consistent with the expected rate of accidental coincidences?*

Pump laser on

Turning on the pump laser produces DC photons from the BBO crystal. The APDs should now be recording simultaneous hits from correlated signal and idler DC photon pairs in addition to any accidental coincidences. With all three APDs still connected to the scalers, measure their singles rates. Now reconnect the circuit as shown in Fig. 4. so that you are again measuring #1#2 and #1#3 coincidences. Measure the accidental coincidence rates.

Q: *From the singles rates calculate the expected number of accidental coincidences for #1#2 and #1#3. Are the measured coincidence rates consistent with the expected rate of accidental coincidences?*

Q: *Are your data consistent with the expectation that the pump laser produces correlated photon pairs in the BBO crystal?*

Q: *Using the 10nm band width of the interference filters in front of the APDs as the uncertainty of the detected photon wavelength, calculate the length of the photon from the uncertainty principle* $\Delta E \Delta t = \hbar$.

Q: *From the posted data sheets find the efficiencies of the interferometer's optical components, and the transmission characteristics of the narrow band pass filter in front of the APDs. Using these data and the singles rate for APD#1 and APD#2 calculate the number of photons per second passing through the interferometer. Using the length of the photon calculated above, estimate the average distance between successive photons passing through the interferometer. Measure the total distance a photon travels in passing through the interferometer. Comment on the probablility of having more than one photon passing through the interferometer at a time.*

5.4 Single Photon Interference (Indistinguishable Paths).

Place an empty filter holder in front of APD#2. This filter holder serves to keep the effective aperture of APD#2 constant when a linear polarizer is placed in this location later.

Look for interference (changes in transmitted intensity) as you vary the path length of one arm of the interferometer. To do so, measure coincidence rates, for #1#2 and #1#3, and singles rate for APD#1 for piezo voltages from 35V to 65V in 1V steps.

5.5 Single Photon Interference (Distinguishable Paths).

Rotate one of the half-wave plates by 45° while leaving the other half-wave plate at 0°. The two paths through the interferometer are now *distinguishable*. That is, which path a photon took could be determined by the photon's polarization.

Measure the coincidence and singles rates again over the same voltage range.

The degree to which the two paths are distinguishable is determined by the relative alignment of the two half-wave plates. If they are exactly 45° apart, the photon polarizations for the two paths through the interferometer will be exactly orthogonal. As a result quantum mechanics predicts that there will be no single photon interference. However, if the two half-wave plates are not precisely 45° apart, the photon polarizations will not be completely orthogonal and you still will observe some single photon interference, but at a reduced amplitude.

Plot your measured coincidence rates against piezo voltage. If your two half-wave plates are set correctly your data should be statistically consistent with zero interference amplitude. If your data still show some interference effect, you will need to search for the correct angle in one degree increments, re-plotting some of the data as you search. It should take no more than 4 or 5 iterations to make the two paths through the interferometer completely distinguishable.

5.6 Single Photon Interference (Quantum Eraser).

(Note: Turn on the HeNe laser an hour before you wish to perform the calibration of Part 5.8, to stabilize the laser output.)

In order to erase the information about which path the photon took, we will place a linear polarizer in front of APD#2. The linear polarizer needs to be adjusted so that its pass axis makes a 45° angle with respect to the polarization axes of the two paths through the interferometer. Use the following procedure to set the pass axis of the linear polarizer.

1. Use a piece of black foam board to block one arm of the interferometer.
2. Replace the empty filter holder in front of APD#2 with a filter holder containing a linear polarizer.
3. Connect the output of APD#2 to the rate meter in the electronics rack. Set the rate meter to an appropriate range. You may wish to use the feature that produces an audible tone whose frequency varies with the count rate.
4. Rotate the polarizer while observing the count rate from APD#2 on the rate meter. Find the two angles on the polarizer filter holder which correspond to the cases when the pass axis of the polarizer is parallel to the polarization of the photons. Make note of these angles.
5. Now move the light blocking foam board to the other arm of the interferometer. Use the rate meter to determine the polarizer angles associated with the polarization axis of the light passing through this arm of the interferometer. The polarizations in the two arms should be orthogonal. Are they? If not, re-adjust the half-wave plate.
6. Use this information to set the polarizer to an angle which is as close as possible to being 45° with respect to the two possible photon polarization axes.

Setting the polarizer to the proper angle makes the two paths indistinguishable once again. (Explain how). Un-block both arms of the interferometer and cover the table. Reconnect APD#2 for coincidence counting. Measure the coincidence rates as a function of piezo voltage and plot your results.

5.7 Indivisible photons or Weak EM waves?

One of the central assumptions in interpreting single photon interference is that light is made up of *indivisible* photons. If this assumption is true then we would expect that light entering the final beam splitter would either be transmitted or reflected, but not both. In this case we would detect a count in APD#2 or #3, but not both.

On the other hand if the light entering the interferometer is a continuous EM wave, one would expect equal amounts of light entering both APD#2 and #3 at the same time.

Modify the circuit of Fig. 4 to measure the coincidence rate #2#3.

Q: Compare this rate to the expected accidental coincidence rate.

Q: Does the evidence point to indivisible photons or to weak EM waves?

If the evidence shows that indivisible photons are involved, then single photon interference is not readily explainable in classical E & M terms!

5.8 Piezo Calibration. (For good stability, allow the HeNe laser to warm up for an hour before use here).

We want to know how much the path length of the one arm of the interferometer changes as a function of the voltage applied to the piezo. To do so, we will direct the beam from a HeNe laser, whose wavelength is 632.8nm, into the interferometer. The intensity of the beam leaving the interferometer can be measured as a function of the piezo voltage. From the resulting spacing of the interference maxima and the wavelength of the laser light, the conversion factor between piezo voltage and change in path length can be calculated.

Use the following procedure to perform this calibration.

1. Turn off the APD detectors. The light from the laser is too bright to use the APDs.
2. Turn off the Pump laser.
3. Direct the beam from the HeNe laser into the interferometer by raising Flip Mirrors #1 and #3 and lowering Flip Mirror #2.
4. Place the ThorLabs photodiode so that it intercepts the HeNe beam that reflects off of Flip Mirror #2. Connect the photodiode to ch1 of the scope. Make sure ch1 is dc coupled. Set the scope to auto-trigger on ch1.
5. Most likely the HeNe beam exiting the interferometer will be too bright and the output of the photodiode will be saturated. Use a neutral density filter to dim the laser beam so the photodiode is no longer saturated, i.e., when the output changes in response to changes in the piezo voltage.
6. Measure the voltage from the photodiode for piezo voltages from 35V to 65V in 1V steps.

6. ANALYSIS.

Your analysis should focus on comparing your data with the quantum mechanical predictions of single photon interference for the three cases studied; indistinguishable paths, distinguishable paths, and erasure of path distinguishing information. A key assumption in the experiments has been that only one photon at a time is in the interferometer. Thus, you should present data which confirm this assumption. The following points should be addressed in your lab report.

- Make a single plot of the #1#2 coincidence rate as a function of piezo voltage for all three cases; indistinguishable paths, distinguishable paths, and eraser. You need only show the data where you achieved maximum extinction of the interference pattern for the distinguishable path case. Fit all three sets of data to the following functional form:

  $$R_C = N\left(1 + D\cos\delta\right)$$
  $$\delta\left(V\right) = A + BV + CV^2$$

  where R_c is the coincidence rate, N is a normalization constant, D is the depth of the interference maxima, V is the piezo voltage. The function $\delta(V)$ allows for the possibility that the displacement of the piezoelectric crystal is not linear with respect to the applied voltage. A, B and C are fit parameters that describe the nonlinearity of the piezo.

  Compare your data with the quantum mechanical predictions for single photon interference for the three cases.

  Show that the reduced amplitude of the restored interference pattern in the eraser case is consistent with the data for the indistinguishable paths case when the loss of photons passing through the linear polarizer is taken into account.
- Plot the #1#2 and #1#3 coincidence rates as a function of voltage for the case when the paths are indistinguishable. The minima (destructive interference) in an interference pattern occur when the path length difference between the two arms of the interferometer is $(n+1/2)\lambda$. When talking about single photon interference this raises the question of what happens to the energy of the photon when it destructively interferes with itself?

That energy must go somewhere! Use the plot of #1#2 and #1#3 to explain what happens to the photon's energy.

- From your data on the detector background singles rates under different lighting conditions, and the rates with the pump laser on, show that the background is statistically insignificant compared to the rates of DC photons.

- Use your data on the two-fold coincidence rates to show that the rate of accidental coincidences caused by background light is consistent with statistical predictions. Compare this with the coincidence rates obtained when the pump laser is on and show that the coincidences caused by the background light are statistically insignificant compared to the DC photon rates. In discussing these first two bullet points, make the case that operating the experiment with the narrow bandpass filters in front of the detectors, with the room lights on and the table covered yields data with an acceptable signal to noise ratio.

- Using the two-fold coincidence data when the pump laser is on, show that the coincidence rate is significantly higher than expected due to accidental coincidences based on the singles rates. Comment on how these data strengthen the argument that the APDs are detecting correlated pairs of DC photons from the BBO crystal when the pump laser is turned on.

- Show that it is statistically unlikely that more than one photon is inside the interferometer at the same time. Using the singles rates in APD#2 and APD#3, the transmission characteristics of the narrow bandpass filters (posted in the lab), and the reflectivities of the optical components that make up the interferometer (also posted in the lab), estimate the total number of photons passing through the interferometer per second. Assuming that the photon are 100μm long calculate the average distance between successive photons. Show that this average distance is large compared to the dimensions of the interferometer.

- Use the #2#3 coincidence measurement to bolster the argument that you are detecting individual photons as opposed to purely classical electromagnetic waves.