Lab 1:
Spontaneous Parametric Downconversion

Lab Ticket -- must be finished before you come to lab. Each group turns in one ticket.

You have a nonlinear crystal which has been cut to downconvert light at 405 nm to signal and idler beams at 810 nm. If the index of refraction of the crystal is 1.659 at 405nm, and 1.661 at 810nm, what angle do the signal and idler beams make with respect to the pump?

Important Safety Tips

- For your safety, **NEVER LOOK DIRECTLY INTO THE LASER.** You should **WEAR THE LASER SAFTY GOGGLES** while in the lab; they will block the intense blue laser light, but still allow you to see.

- **REMOVE YOUR WATCH OR ANY OTHER SHINY JEWLERY THAT'S ON YOUR HANDS OR WRISTS**. A reflection off of a shiny surface can be accidentally directed to someone's eye.

- For the safety of the equipment, **NEVER TURN ON THE ROOM LIGHTS WHILE THE PHOTON COUNTING MODULES ARE ON.**

  There is a small box on the table that has a 3-position switch on it. These boxes are connected to the single photon counting modules (SPCM's). The switch positions are labeled "OFF", "GATE" and "ON" (or just "OFF" and "ON"). **This switch must be in the OFF position when the room lights are on**. There is a separate switch to turn on the power to the modules; it is OK for the power to be on, but the detectors themselves must be OFF.

- In general, if the manual is not clear, or you're not completely sure how to do something, **PLEASE ASK FOR HELP**.

While in the Lab

You should have some sort of notebook to write things down while you are in the lab. You will notice that there may be questions you will be asked to answer in the course of these laboratories. You will not have time to answer all of these questions while in the lab, but you should record all of the necessary observations that you will need in order to answer them. Your time in the lab is limited; make and record observations in the lab, but perform calculations when the lab is over.

It will also be helpful for you to record in your notebook the names of the data files you generate, along with the parameters you used and the key results you obtained. It can be quite frustrating to know that you have a good data set, but not remember which one it is, or what parameters you used to obtain it.

I. Introduction

All of the experiments that you will perform this semester will be based on the process of spontaneous parametric downconversion. This physical process comes in many variations, but at its most basic level it is a process in which light of one frequency is converted into light of a different frequency. Any optical process which changes the frequency of a light beam is inherently *nonlinear*. Most of the other optical processes you are probably familiar with (absorption, reflection, refraction, polarization rotation, etc.) are *linear* processes; they may affect many properties of a light field, but linear processes can never change the frequency of light.
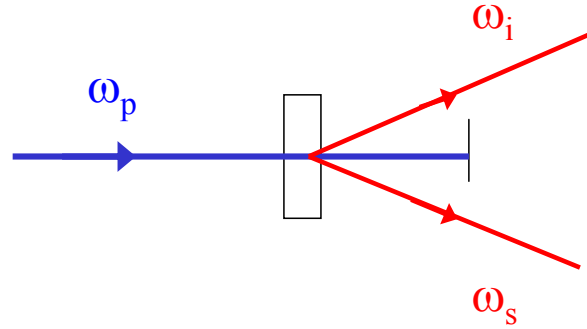

Fig. 1 Spontaneous parametric downconversion.

In the process of spontaneous parametric down conversion, shown schematically in Fig. 1, a single photon of one frequency is converted into two photons of lower frequency (by approximately a factor of 2) in a nonlinear crystal. While downconversion is extremely inefficient (10's of milliwatts of input power generate output beams that must be detected using photon counting) it is much more efficient than other sources of photon pairs (for example, atomic emission of 2 photons).

The input wave is referred to as the pump (at angular frequency ω_p), while the two outputs are referred to as the signal and idler (at angular frequencies ω_s and ω_i). This process is said to be "spontaneous" (as opposed to "stimulated") because there are no input signal and idler fields, they're generated spontaneously from the pump in the crystal. The process is "parametric" because it depends on the electric fields, and not just their intensities. This means that there is a definite phase relationship between the input and output fields. It is called "downconversion" because the signal and idler fields are at a lower frequency than the pump field.

Energy conservation requires that

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

$$\omega_p = \omega_s + \omega_i \ . \tag{1}$$

Momentum conservation is equivalent to a classical condition known as "phase-matching", which requires that the wave vectors of the input and output fields satisfy

$$\vec{\mathbf{k}}_p = \vec{\mathbf{k}}_s + \vec{\mathbf{k}}_i \ . \tag{2}$$

The frequencies and wave-vectors are not independent of each other, and are related by the dispersion relationship

$$k_p = \frac{n_p(\omega_p)\omega_p}{c} \ , \tag{3}$$

where $n_p(\omega_p)$ is the index of refraction of the crystal at the pump frequency, and similarly for the signal and idler waves.

In type I downconversion, which is what we will use in our experiment, the signal and idler beams are polarized parallel to each other, and their polarization is perpendicular to that of the pump; all polarizations are linear. By proper orientation of the pump beam wavevector $\vec{\mathbf{k}}_p$ and polarization with respect to the optic axis of the crystal, it is possible to satisfy the constraints imposed in Eqs. (1)-(3).

Fig. 2 Correlations between the frequencies of the signal and idler beams. If the idler frequency increases, the signal frequency decreases, and vice versa.

The crystal we use is beta-Barium Borate (BBO). In our experiments the pump laser has a wavelength of around 405nm, while the signal and idler beams are at 810nm (twice the wavelength, half the frequency). In order to separate signal and idler, they are chosen to make a small angle (a few degrees) with the pump beam; so the signal comes out a few degrees from the pump, and the idler comes out a few degrees on the other side of the pump. Since only the relative angles between the pump, signal and idler are important, the signal and idler beams are emitted into cones surrounding the pump beam (see, for example, Ref. 1).

However, for a given crystal orientation, there is not a unique solution to the constraints imposed in Eqs. (1)-(3). The sums of the frequencies and wavevectors are constrained, but not the individual frequencies and wavevectors. As shown in Fig. 2, if the idler frequency is somewhat more than half the pump frequency it is possible for energy to be conserved, Eq. (1), if the signal frequency is an equal amount less. In order for momentum to be conserved, Eq. (2), the signal then makes a slightly greater angle with respect to the pump, and the idler makes a slightly less angle. Thus, the light coming out of a down conversion crystal is emitted into a range of angles (up to several degrees), and wavelengths (on the order of 10's of nm, centered about twice the pump wavelength.)

While the emitted photons are allowed to come out in many directions and with many frequencies, they always come in signal-idler pairs, with the pairs satisfying the constraints in Eqs. (1)-(3). It is also the case that these photon pairs are emitted at the same time (to a very high precision); to distinguish specific pairs of photons we use this fact. We find the pairs by using a technique called "coincidence counting." If two photons are detected within a narrow time interval (about 8 ns wide in our experiments) we say that they are coincident, and assume that they constitute a signal-idler pair.

In this lab we'll be exploring things like the momentum conservation rule and the precision of the timing of the photon pairs.
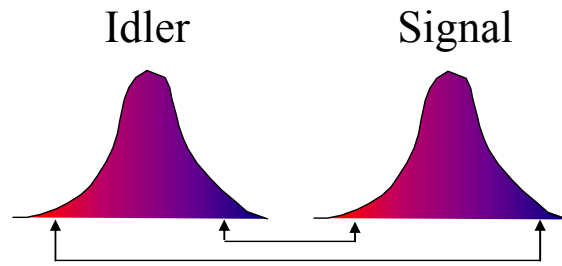
The experimental apparatus is shown in Fig. 3. The signal and idler photons are collected with lenses, coupled into optical fibers and directed to single photon counting modules (SPCM's) where they are detected. Not shown in this figure are colored glass filters, which are in-line with the fibers, between the collection lenses and the SPCM's. These are RG780 filters that block wavelengths shorter than 780nm, and transmit wavelengths longer than this. Their purpose is to transmit the downconverted light, while blocking scattered blue pump light, and the green light we use to illuminate the laboratory.

The SPCM's output an electrical pulse every time they detect a photon. These pulses then go the coincidence counting unit (CCU), shown in Fig. 4. The CCU takes inputs from up to four detectors, and uses a programmable logic chip (a field programmable gate array, or FPGA) to implement eight 32-bit counters.
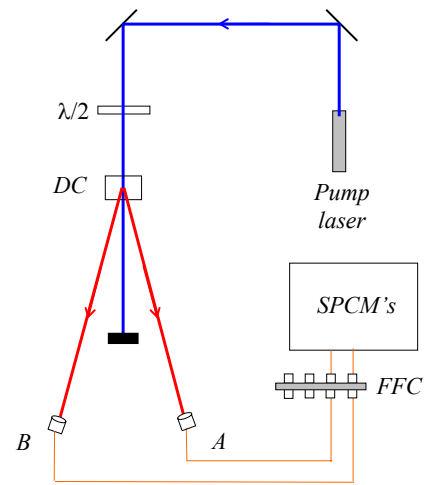

Fig. 3 The experimental arrangement. Here $\lambda/2$ denotes a half-wave plate, DC denotes the downconversion crystal, FFC denotes fiber-to-fiber coupler, and SPCM's denotes the single photon counting modules,

Four of the counters (Counter $0 - 3$) are for the input signals (called singles counts), while the other four counters (Counter $4 - 7$) count arbitrary 2-, 3-, or 4-fold coincidences. Switches determine which coincidences are counted, as shown in Fig. 5. Data is streamed from the CCU to a host computer over an RS232 serial interface.
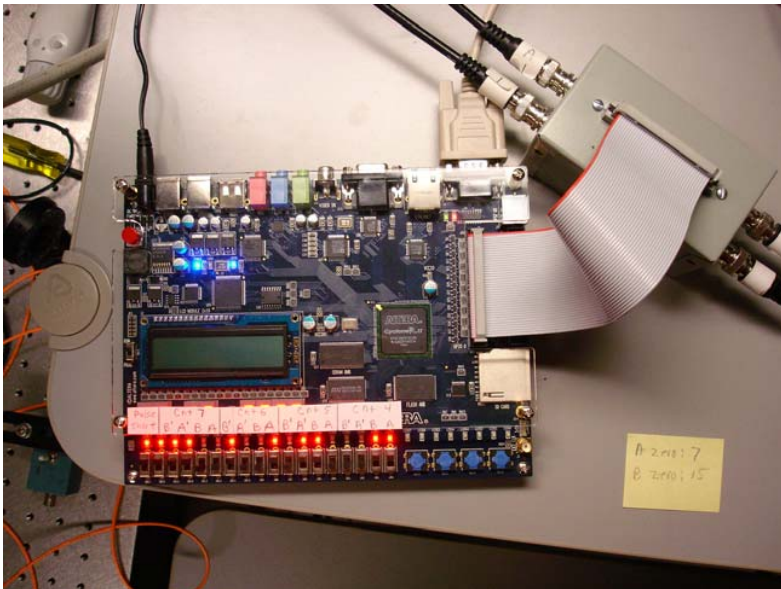

Figure 4: The CCU.

Figure 5: How the switches determine which coincidence is counted. Here, Counter 4 will count AB coincidences, and Counter 5 will count A'B coincidences.

The most crucial aspect of the experiment is properly coupling the signal and idler beams into the fibers, and maximizing the number of coincidence counts obtained between the signal and idler beams. This alignment will be your primary task in this lab.

We speak of aligning the **A**-detector (for example), but really we mean aligning the lens and optical fiber that deliver the downconverted light to the detector. Shown in Fig. 6 are the mounts, lenses and fibers for this experiment. The bases which hold the mounts slide along a ruler, which is fastened to the table. This allows reasonably precise translation of the mounts, in order to position them at the correct angles to detect the downconverted photons.
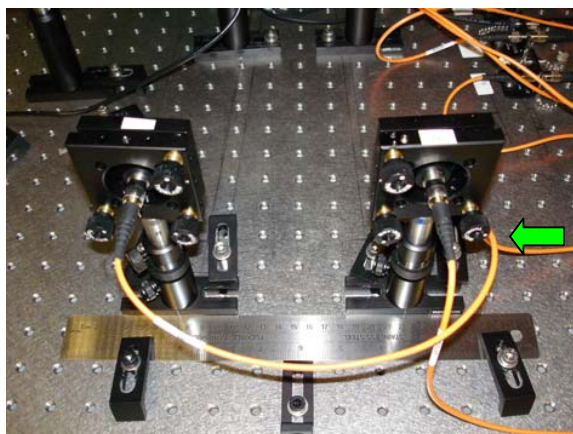

Fig. 6   View from the back side of the mounts, lenses and fibers which collect the downconverted light. The ruler is used to help position things. The green arrow shows the knob you use to adjust the horizontal tilt of the A-detector.

II. Aligning the A-Detector

The downconversion crystal we will use is cut so that the signal and idler beams make nominal 3° angles with respect to the pump beam. So, the first order of business is to place detector **A** so that it makes a 3° angle with the pump beam, and get it facing the downconversion crystal. This coarse alignment is done by shining a laser beam backward through the fiber that collects the light for the **A**-detector, and aligning this laser on the crystal. This beam shows us where the **A**-detector is "looking", so if it shines on the crystal we should be able to see the downconverted light that comes from it.

If at any time in this procedure you have trouble, please don't hesitate to ask for help.

- Please wait for me to show you how to turn things on, etc.

- **Double check that the detectors are turned off.**

- **Insert a beam block in the blue pump beam.**

- When you first get to the lab, the fiber from the collection optics for the **A**-detector should be connected to a fiber-coupled laser, as shown in Fig. 7.
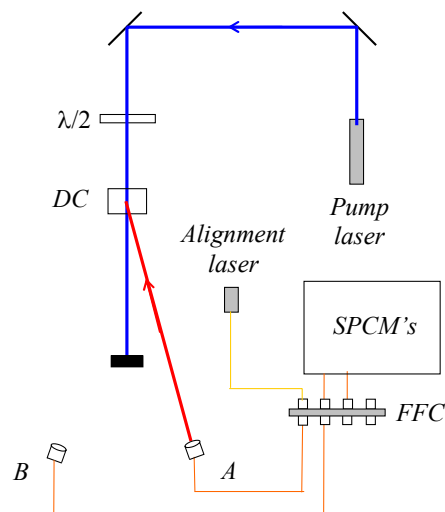

Fig. 7.   Using the alignment laser. It should travel backwards from the collection optics, and onto the downconversion crystal.

- Place the **A**-detector so that it makes an angle of approximately 3° from the pump laser, and that its base is pushed up against the ruler (as shown in Fig. 4).

- Turn on the alignment laser (**maximum current of 50 mA**), then adjust the vertical and horizontal tilt of the mount, using the knobs on the back, so that the beam strikes the center of the downconversion crystal. The laser light appears dim because it is at a wavelength your eye is not very sensitive to.[*] If you stick white paper in the beam you should be able to see it with the room lights out. You should be able to see it very brightly using the CCD camera and TV monitor.

- Gently screw the **A**-detector mount to the table (don't need to tighten it down super-tight yet), and double check that the laser is shining on the center of the crystal.

- **Turn off the alignment laser.**

- Unscrew the **A**-fiber from the alignment laser, and connect it to the fiber leading to the **A**-detector. **Please do this carefully** so that you don't scratch the fiber tip.

The **A**-detector is now coarsely aligned. The next step is to perform the fine alignment to maximize the signal on this detector.

- Start by double-clicking the "Coincidence.llb" icon on your desktop. This opens a LabView library in a window. Then click on the "Coincidence.vi" icon in the upper left of this window.

This launches LabView and loads the data acquisition program. Documentation for the program is given in Appendix A.

- Run the program by clicking the Run icon (the arrow in the upper left corner of the window.)

- If you ever need to stop the program, do so by pushing the **STOP** button in the upper left. Do not simply close the window without stopping -- if you do this the program does not exit gracefully. At the very least you'll need to restart LabView; you may need to reboot the machine.

After a few seconds the program is running, reading the counters, and updating the screen in real time--although this may not be obvious at first because the detectors should still be turned off.

- Remove the beam block from the blue pump beam.

- Make sure the room lights are turned off (it's OK for the green safe flights to be on) and turn on the detectors.

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[*]The alignment laser puts out several mW of light at about 780nm. Your eye is not very sensitive to this light, but it IS a fairly intense beam, and you should **be very careful not to look directly into it. Also, take care not to accidentally couple the laser light into the fiber leading to the SPCM's.** The filters will not block much light at this wavelength, and the SPCM's are VERY sensitive to it and could easily be damaged. It is wise to **make sure that the SPCM's are turned off while the alignment laser is turned on**.

Now the indicators on the screen should be changing, and it should be more obvious that the program is running. The mode the program is currently running in is useful for "tweaking": adjusting the various parameters and seeing how they affect the measured count rates. Once things are adjusted how you want them to be, you press the **Take Data** button and the program switches to data record mode, where the data is saved to a file on the disk.

- Make sure the **Experimental Setup** dial is set to **Coincidence** (if it isn't, click on the dial and rotate it), and that **Update Period** is set to 0.1 or 0.2s (if it isn't, highlight the value, type "0.2", and hit <Enter>).

You should see some **A** counts, but probably not a large number. For the moment don't worry about the **B** counts or the **AB** coincidence counts.

- Set the full scale reading on the "thermometer" measuring the **A** counts to be about 3 times larger than the present count rate. The idea is that you're going to be trying to increase the **A** count rate, so you want to be able to have some room on the display to see the count rate increase.

- Slowly adjust the horizontal tilt of the **A** detector mount while observing the count rate. If moving in one direction decreases the counts, go the other way. Keep moving back and forth until you have maximized the count rate. If you need to change the full-scale reading on the "thermometer" while performing this adjustment then do so.

- Repeat the last step, but using the vertical tilt adjustment.

Now the detector is looking directly back at the downconversion crystal, but we need to optimize the angle that the detector makes with the pump beam.

- In your lab notebook, record the position of the **A**-detector (using the ruler as a guide) and the detection rate.

- While holding the mount in place with one hand, keeping it pushed against the ruler, unfasten the screw that secures the mount to the table. Keeping one hand holding the mount in place on the table, use your other hand to readjust the horizontal tilt so that the **A** count rate is maximized. Note that the vertical adjustment should not need to be changed

- Slide the detector mount 0.5 or 1 mm in either direction, and readjust the tilt to maximize the **A** detection rate. Again record the position and the rate.

- Continue to move and tilt the detector (with ever finer adjustments) until you find an alignment which maximizes the **A** count rate. Note that each time you slide the detector you should maximize the count rate by adjusting the tilt before you start to slide it again.

- Carefully screw the mount securely to the table, then give one final adjustment of both the vertical and horizontal tilts.

- Record in your notebook the position of the **A**-detector and the detection rate.

- **Turn off the detectors.**

- Q1: What is the angle of the **A**-detector from the pump beam at this optimal position?

At this point I'd like you to find me so that I can see how well you've done with this alignment.

III. B-Detector Alignment

The idea now is to place the **B** detector in the proper location to maximize the number of **AB** coincidence counts. Remember that although the downconverted light is emitted in many directions, individual pairs of photons have well defined angles, as determined by Eq. (2). Since the **A** detector is now fixed, it is necessary to place to **B** detector in the correct spot to properly detect the pair photons. Thus, we are interested in maximizing the **AB** coincidence counts, not the singles counts on the **B** detector.

- **Make sure the detectors are turned off.**

- **Insert a beam block in the blue pump beam.**

- Make sure that Counter 4 of the CCU is set for **AB** coincidences.

- The fiber from the **B** collection optics leads to a fiber-fiber connector, where it joins another fiber which leads to the filters and a SPCM. Unscrew the fiber coming from the **B** collection optics, and connect it instead to the fiber leading from the alignment laser (similar to Fig. 7, but with **B** connected instead of **A**). **Take care when you do this.**

- Turn on the alignment laser (**maximum current of 50 mA**), and light from this laser will shine backward through the **B**-fiber and emerge as a collimated beam from the fiber coupling lens attached to the end of the fiber.

- Place the **B** detector mount so that the base pushes the up against the ruler, as shown in Fig. 6. Begin by locating the **B** detector so that it makes roughly the same angle from the pump beam as the **A** detector.

- Adjust the tilt of the mount so that the laser beam shines onto the downconversion crystal in order to coarsely align the **B** detector. Gently tighten the mount to the table.

- **Turn off the alignment laser.**

- Carefully unscrew the **B**-fiber from the alignment laser, and connect it to the fiber leading to the **B**-detector.

- Remove the beam block from the blue pump beam.

- Make sure the room lights are turned off and turn on the detectors.

- Slowly adjust the horizontal tilt of the **B** detector mount while observing the **AB** coincidence count rate (NOT the **B** singles rate). Keep adjusting until you have maximized the coincidence count rate. Once again you may need to change the full-scale reading on the **AB** "thermometer" while performing this adjustment.

- Repeat the last step, but using the vertical tilt adjustment.

- In your lab notebook, record the position of the **B**-detector and the **B** and **AB** detection rates.

- While holding the **B** mount in place with one hand, keeping it pushed against the ruler, unfasten the screw that secures the mount to the table. Keeping one hand holding the mount in place on the table, use your other hand to readjust the horizontal tilt so that the **AB** coincidence count rate is maximized. Note that the vertical adjustment should not need to be changed

- Now repeat the procedure you did before, but with the **B** detector. Slide the mount 0.5 or 1 mm in either direction, and readjust the tilt to maximize the **AB** coincidence rate.

- Continue to move and tilt the detector until you find an alignment which maximizes the coincidence count rate. You shouldn't have too much trouble obtaining a maximum coincidence rate of 1000 cps (counts-per-second -- note the units) or better.

- Record the position of the **B** detector, and the optimal **B** and **AB** count rates.

- Q2: What is the angle of the **B**-detector from the pump beam at this optimal position?

IV. Angular Correlations – Momentum Conservation

Having done the above you should have the optimal alignment, and some idea of the range over which you can obtain coincidences. Now it's time to make a careful study of how the coincidence rate depends on angle. You will scan over a 1° range of angles, centered about the optimal angle. I would like you to take at least 10 data points across this range, calculating the average and standard deviation of the coincidence rate at each point. You will use the **Take Data** feature of the program to do this.

- Place the detector so that it is at the smallest angular position you will acquire data at, and adjust the tilt to optimize the coincidence rate.

- In the **Data Taking Parameters** section of the program set **Update Period (Data Run)** to 1.0s, and **Number of Points** to 10. Now press the **Take Data** button.

A new window will automatically open as the computer switches to data taking mode. The computer will automatically take 10 measurements with 1.0s counting windows, plot the data on the screen, calculate the mean and standard deviation of the coincidence rate, and save all the data to a file. The data file is automatically named according to the date and time.

- In your notebook record the filename, important parameters (e.g., the location of the detector), and the results.

- Once you have written down all of these parameters, you can close the window of the data recording program.

- Check the data file you just created. There is a shortcut to the Data folder on your desktop. Inside the Data folder find the folder with today's date on it, and your file should be in there. Open it up and look at it (it's easiest to use Excel—right click on the file and choose "Open With" Excel); the info in the file should agree with what you wrote in your notebook. Despite the fact that most of this information is stored in the computer (it doesn't know the detector position, for example), the notebook is handy because you can easily find the names of the good data sets, and don't have to open lots of files to find what you're looking for.

When you are all done with the lab, remember to save all your data on your network drive. I suggest you use the Web version of Netfiles.

- Repeat the above process for at least 10 data points over a 1° range of angles. At the two extremes of your data, the coincidence rates should be less than 10% of the maximum rate; if this is not the case you should take more data at larger angles.

- When you're all done taking data, place your detector at the optimum position, and lock it to the table with the clamps.

After you leave the lab create a graph of coincidence count rate versus angle, including error bars.

- ♦ Q3: Approximately what is the full width at half maximum (FWHM) of this distribution?

V. Polarization

Now you're going to examine the polarization properties of your downconversion source.

- Place the linear polarizer in the blue pump beam (after the crystal) and rotate it to maximize the amount of blue light transmitted through the polarizer—just look at the blue light on a screen and maximize its brightness. You have now oriented the polarizer so that it is parallel to the polarization of the blue pump beam.

- Move the polarizer so that it is in front of the **A**-collection optics.

- ♦ Q4: What happens to the count rate on the **A**-detector when you insert this polarizer? What does this say about the relative orientation of the polarization of the blue beam and the polarization of the beam hitting the **A**-detector?

- Repeat this measurement by placing the polarizer in front of the **B**-collection optics.

- ♦ Q5: What happens to the count rate on the **B**-detector when you insert the polarizer? What does this say about the relative orientation of the polarization of the blue beam and the polarization of the beam hitting the **B**-detector?

- Remove the polarizer. Rotate the half-waveplate that the blue beam passes through in front of the donwconversion crystal while looking at the count rates.

- ♦ Q6: How many degrees do you need to rotate the waveplate in order to minimize the count rates? By how far has the polarization of the blue beam been rotated? What does this say about the pump wave polarization and the crystal orientation?

- Rotate the waveplate back to maximize the count rates.

VI. Timing

As discussed above, the photon pairs are produced not only with well defined angles, but also at well defined times. Indeed, the two photons are produced at the same time. We can't say that they are produced at *exactly* the same time, because, as you will learn in class, there is an uncertainty relationship between energy and time. For our experimental parameters the uncertainty in time is on the order of 10fs -- a time that is much shorter than our experimental

apparatus can resolve. Here we will be able to show that this uncertainty is less than about a nanosecond.

In order to perform this measurement you'll use an instrument known as a Time-to-Amplitude Converter (TAC), which measures the time interval between two events. In our case the two events are the detections of two photons. One detector is connected to the START input of the TAC, while the other is connected to the STOP input. The TAC outputs a voltage pulse whose height is proportional to the time interval between these events. We ensure that the STOP always comes after the START by inserting an extra length of electrical cable between the STOP detector and the TAC. We will thus measure a time interval that is offset from zero by this electrical delay; we are not interested in this offset, but rather in the width of the distribution of the arrival times.

The output pulses from the TAC are most easily analyzed with an instrument known as a multi-channel analyzer (MCA). An MCA reads in the voltage pulses and displays a histogram of the pulse heights. Because we can calibrate the TAC, this is essentially a measurement of the distribution of time intervals.

- Find me so I can help you in hooking the detectors up to the TAC.

- **Close the Coincidence.vi** – it cannot be in memory at the same time as the MCA.vi.

- Start by double-clicking the "MCA.llb" icon on your desktop. This opens a LabView library in a window. Then click on the "MCA.vi" icon in the upper left of this window. Documentation for this program is given in Appendix C.

- This program updates the screen after a certain number of pulses are measured, not after a certain time interval. So, if nothing happens after a few seconds it probably means that there are no voltage pulses present. Make sure that the lights are off, and the detectors are on.

- You should see a sharp peak appear in the distribution on your screen. Place the cursors on either side of this peak, then click **Zoom to Cursors** too zoom in on it.

- Click the **Clear Buffer** button to see what it does.

- Hit the **Clear Buffer** button, accumulate some data so that you can clearly see the peak. Push the **Save Data** button to save the data to a file.

After you leave the lab, create a graph displaying this data. Turn this graph in with your lab report. Don't necessarily show all the data, but show about a 10 ns window around the coincidence peak.

- Q7: Approximately what is the full width at half maximum (FWHM) of this distribution?

- Q8: How wide a time window would you need to count essentially all of the coincidences, but as little as possible of the background?

- Q9: Our coincidence circuit has a coincidence window of about 8 ns (assume it's centered about the peak). Given this information, estimate what fraction of the coincidences that are measured are true coincidences, and what fraction are "accidental" coincidences due to the background. Explain how you came up with this estimate.

VII. Write-up

I only need one report per group.

Your write-up should include:

- Answers to all questions.

- A brief (one to two page) write-up describing what you did in the lab, and summarizing your results. In your report I'd like you to discuss the resolution of the measurements. What do you think limits the width of the coincidence peaks--both in angle and in time?

- Graphs of your data.

References:

[1] D. Dehlinger and M. W. Mitchell, "Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory," Am. J. Phys. **70**, 903-910 (2002).

Lab 2:
Proof of the Existence of Photons

Lab Ticket -- must be finished before you come to lab. Each group turns in one ticket.

Read Ref. [2] -- at least the introduction and theory sections.

Using the expression for $g^{(2)}(0)$ in terms of experimentally measurable quantities, explain why we hope to measure $g^{(2)}(0)=0$ in the single-photon experiment. Why do we expect measure $g^{(2)}(0)=1$ for the 2-detector experiment?

Important Safety Tips

- For your safety, **NEVER LOOK DIRECTLY INTO THE LASER.** You should **WEAR THE LASER SAFTY GOGGLES** while in the lab; they will block the intense blue laser light, but still allow you to see.

- **REMOVE YOUR WATCH OR ANY OTHER SHINY JEWLERY THAT'S ON YOUR HANDS OR WRISTS**. A reflection off of a shiny surface can be accidentally directed to someone's eye.

- For the safety of the equipment, **NEVER TURN ON THE ROOM LIGHTS WHILE THE PHOTON COUNTING MODULES ARE ON.**

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- In general, if the manual is not clear, or you're not completely sure how to do something, **PLEASE ASK FOR HELP**.

I. Introduction

First we should define what we mean by "proving" photons exist. Classically, light is an electromagnetic wave. Quantum mechanically, light has both wave-like and particle-like properties, and the quanta are called photons. So, to prove that light is made of photons you want to do an experiment which makes this granular nature of the field apparent.

However, this is not enough. We never measure light directly, but always measure the current from a detector instead. It is possible for the granularity of our measurements to be caused by the discrete nature of the electrons in our detector. Assume a classical wave is incident on a detector. How do we determine whether the granularity of our measurements is due to the discreteness of electrons in the detector, or the discreteness of photons in the field? There is no easy way to do this. Observing granularity in measurements of a field is a necessary,
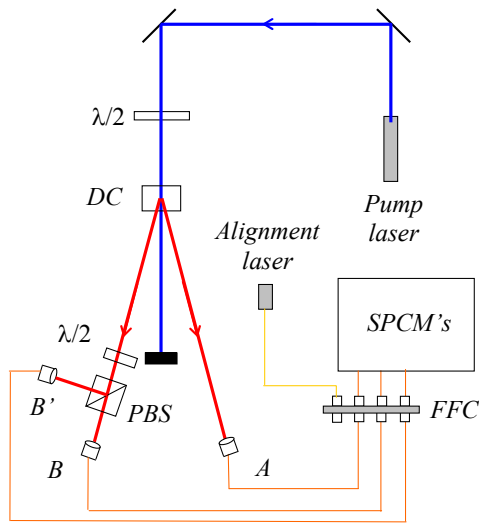
Fig. 1. The experimental apparatus. In addition to the pieces of equipment introduced in the last lab, here we have a polarizing beamsplitter (PBS).
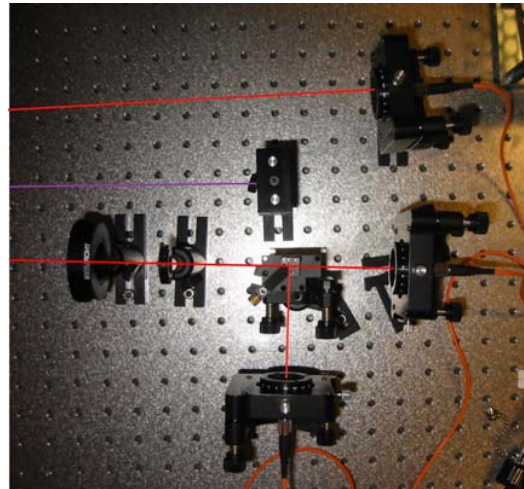

Fig 2. Picture showing the waveplate, PBS, and the collection optics. Beam paths are shown for clarity.

but not a sufficient, condition for the existence of photons. Granularity motivates the existence of photons, but does not prove it.

Since photons are inherently a quantum mechanical object (remember, classical waves aren't made of photons), an experiment which requires a quantum mechanical explanation would imply that the field is made of photons. In other words, if we do an experiment that we cannot explain classically, it means there is more to the field than just classical waves. To be precise, the experiment we will do distinguishes between quantum mechanical and classical theories of the electromagnetic field. If classical waves cannot explain the results, then we take this to mean that photons exist.

You will be performing an updated version of the experiment performed originally by Grangier, Roger and Aspect [1-3]. The experimental apparatus is shown in Figs. 1 & 2. The basic idea is to show that if a single photon is incident on the beamsplitter, it can be detected at **B**, or at **B'**, but not both. We ensure that a single photon is incident on the beamsplitter by conditioning all of the measurements on a detection at **A**.

The measurements are quantified using a parameter called the degree of second-order coherence, $g^{(2)}(0)$. Instead of repeating here what's already been written elsewhere, you should read Ref. [2], which provides the theoretical background for this experiment. In that article you'll learn that a classical wave theory requires $g^{(2)}(0) \geq 1$. This is an instance of a classical inequality, of which there are many in physics. There are situations in which quantum mechanics can violate classical inequalities, and in these cases we say that we are observing strictly quantum mechanical phenomena. For this experiment, if we measure a value of $g^{(2)}(0) < 1$, then the field cannot be explained classically, and we have proven the existence of

photons. The quantum state which yields maximum violation of this classical inequality is the single photon state, for which the quantum prediction is $g^{(2)}(0)=0$.

The above described experiment uses three detectors to measure $g^{(2)}(0)$. I look at this as measuring $g^{(2)}(0)$ for the signal beam striking the beamsplitter, *conditioned* on a detection in the idler beam. The conditioning is key -- it's what prepares the signal beam in a single photon state. Without this conditioning the beam striking the beamsplitter is purely classical. To prove this you will also perform a two-detector, unconditional measurement of the signal beam, for which you should observe $g^{(2)}(0)\geq1$.

II. Theory

There's a lot of detailed the theory in Ref. [2], especially on the three-detector measurements. However, there's not much information there on two-detector measurements, so I'll give some detail on that here.

Lets start with the two-detector theory. When $g^{(2)}(0)$ is measured using photoelectric detection, it can be written in terms of the probabilities of individual photodetections as

$$g^{(2)}(0) = \frac{P_{BB'}}{P_B P_{B'}} \quad \text{(2-detector)},$$

(1)

where P_B ($P_{B'}$) is the probability of a detection at detector **B** (**B'**) in a time interval Δt, and $P_{BB'}$ is the probability of making detections at both **B** and **B'** in the same time interval (i.e., a coincidence detection). We can express the probabilities in terms of measured count rates. For example, the probability of a detection at **B** in a short time interval Δt is simply given by the average rate of detections, multiplied by Δt. The average rate of detections at **B** is just the number of detections N_B divided by the counting time T that we are averaging over. The probabilities for **B** detections and **BB'** coincidences are given similarly:

$$P_B = \left(\frac{N_B}{T}\right)\Delta t, \qquad P_{B'} = \left(\frac{N_{B'}}{T}\right)\Delta t, \qquad P_{BB'} = \left(\frac{N_{BB'}}{T}\right)\Delta t$$

(2)

Substituting this into Eq. (1), we get

$$g^{(2)}(0) = \frac{N_{BB'}}{N_B N_{B'}}\left(\frac{T}{\Delta t}\right) \quad \text{(2-detector)}.$$

(3)

For measuring the conditional $g^{(2)}(0)$ using three detectors, all of our probabilities are further conditioned upon a detection at **A**. In this case we have [in place of Eq. (1)]

$$g^{(2)}(0) = \frac{P_{ABB'}}{P_{AB} P_{AB'}} \quad \text{(3-detector)},$$

(4)

where $P_{ABB'}$ is the probability of threefold detection. Since we are not interested in any events unless detector **A** fires, the number of detections at **A**, N_A, serves as the number of trials which we can use to normalize our probabilities:

$$P_{AB} = \frac{N_{AB}}{N_A}, \qquad P_{AB'} = \frac{N_{AB'}}{N_A}, \qquad P_{ABB'} = \frac{N_{ABB'}}{N_A} \tag{5}$$

Using these probabilities $g^{(2)}(0)$ for the three-detector measurements becomes

$$g^{(2)}(0) = \frac{N_A N_{ABB'}}{N_{AB} N_{AB'}} \quad \text{(3-detector)} . \tag{6}$$

This is the expression from Ref. [2].

III. Getting Started

In Lab 1 you maximized the coincidence count rate between detectors **A** and **B**. When you come into the lab, that much of the alignment will already have been done. Your task this week will be to insert a beamsplitter in the signal beam, and to align detector **B'**. Once this is done you'll be able to measure $g^{(2)}(0)$, and show that light is made of photons.

- Please wait for me to help you turn things on, etc.

- The CCU should be set to measure the following coincidences: Counter 4 - AB; Counter 5 - ABB'; Counter 6 - AB'; Counter 7 - BB'.

- Double-click the "Coincidence.llb" icon on your desktop. This opens a LabView library in a window. Then click on the "Coincidence.vi" icon in the upper left of this window.

- Set **Experimental Setup** to **g(2)(0) 3-det,** and **Update Period** to 0.2s. In the pane that displays the graphs, choose the **AB & AB'** tab.

- The **ABB' Coincidence Window (ns)** parameter tells the computer the effective time window for the three-fold coincidence determination. In three-detector measurements this parameter is needed to calculate the expected value for $g^{(2)}(0)$. Ask your instructor for the precise value; it should be on the order of 5-10 ns for the coincidence circuit we're using.

- Make sure that the lights are out, and then turn on the detectors.

- Adjust the tilts on the **A**-detector to maximize the **A** counts.

- Adjust the tilts on the **B**-detector to maximize the **AB** coincidence counts. You should notice more than 1000 **AB** coincidences per second; **if you don't, ask for help**. The key here is that it should already be aligned, and I don't want you to have to waste time realigning the **A** and **B** detectors.
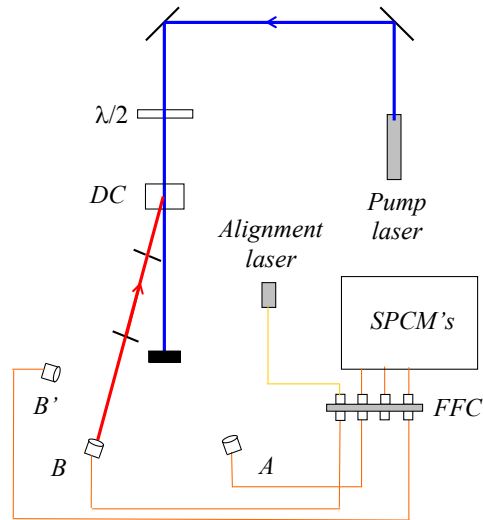
- **Turn off the detectors.**

IV. Aligning the Irises and Beamsplitter

Before going on to the next step, be sure you remember how to carefully connect fibers to the fiber-fiber coupler, and how to use the alignment laser.

- **Make sure the detectors are off.**

- **Insert a beam block in the pump beam.**

- The fiber from the **B** collection optics leads to a fiber-fiber connector, where it joins another fiber which leads to the filters and a SPCM. Unscrew the fiber coming from the **B** collection optics, and connect it instead to the fiber leading from the alignment laser, as shown in Fig. 3. **Take care when you do this.**

- Turn on the alignment laser (**maximum current of 50 mA**), and light from this laser will shine backward through the **B**-fiber and emerge as a collimated beam from the fiber coupling lens attached to the end of the fiber; see Fig. 3.[*] The laser light appears dim because it is at a wavelength your eye is not

Fig. 3. Using the alignment laser. It should travel backwards from the collection optics, through the irises, and onto the downconversion crystal.

very sensitive to. If you stick white paper in the beam you should be able to see it with the room lights out. You should be able to see it very brightly using the CCD camera and TV monitor. If the laser light is not shining backwards onto the downconversion crystal, ask for help.

- First you want to center 2 irises on the alignment beam. One should be about a foot (maybe a bit more) away from the detector, and the other about a foot (maybe a bit less) away from the downconversion crystal. Either by eye, or using the CCD camera, adjust the height and position of the irises so that the alignment beam passes through their centers. You should be able to close the irises down to about 2mm and still get nearly all the beam through. Once the irises are centered on the beams, lock them to the table.

- Make sure that the iris near the downconversion crystal does not block the beam going to the **A** detector. You can check this by letting the blue beam through and seeing where it hits the iris. The **A** beam should make roughly the same angle with the pump as the **B** beam, so you should have a pretty good idea of where it's at with respect to the iris.

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[*]The alignment laser puts out several mW of light at about 780nm. Your eye is not very sensitive to this light, but it IS a fairly intense beam, and you should **be very careful not to look directly into it. Also, take care not to accidentally couple the laser light into the fiber leading to the SPCM's.** The filters will not block much light at this wavelength, and the SPCM's are VERY sensitive to it and could easily be damaged. It is wise to **make sure that the SPCM's are turned off while the alignment laser is turned on**.

- Insert the polarizing beamsplitter (PBS) about 3-4 inches away from the **B** collection optics (Fig. 2). Make sure it is oriented so that light coming from the downconversion crystal will be reflected toward the edge of the table. Make sure that the beam passes through the center of the beamsplitter.

- Orient the beamsplitter so that its face is perpendicular to the beam. Do this by using the CCD camera to look at the back-reflection from the beamsplitter, which shines back toward the collection optics. Orient the beamsplitter so that this back-reflection goes straight back on top of the incident beam. Screw the beamsplitter mount to the table.

Fig. 4. Aligning the B' detector.

- Insert the half-waveplate an inch or two in front of the beamsplitter. Again, center it, orient it perpendicular to the beam, and screw it to the table.
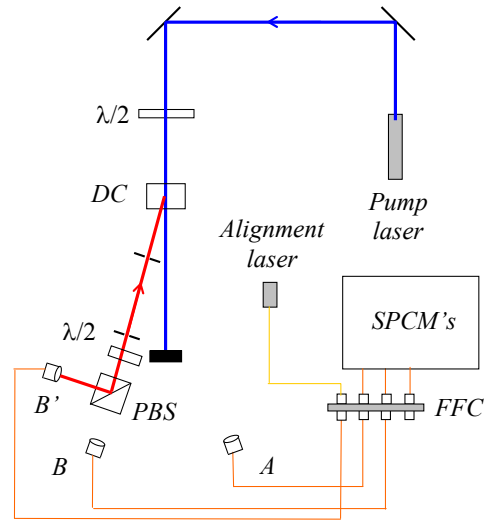
V. Aligning the B' Detector

The next part of the laboratory is probably the most difficult. You will be aligning the **B'** detector so that it collects light from the same beam as the **B** detector. The better job you do aligning this detector, the more light you will collect, the higher your signal-two-noise ratio will be, and the better the results you will obtain.

- Place the mount with the **B'** collection optics on the reflection side of the beamsplitter, about an equal distance from the beamsplitter as the **B** collection optics (Fig. 2). Don't screw it down yet.

- Unscrew the **B**-fiber from the alignment laser, and reconnect it to the fiber leading to the detector. Connect the **B'**-fiber to the alignment laser, as shown in Fig. 4. At this point the beam won't go back through the irises.

- The task now is to get the alignment laser to shine back through the irises and onto the downconversion crystal. By moving the mount sideways (perpendicular to the beam), rotating it, and adjusting the vertical tilt, position it as well as you can to shine the light back through the two pinholes. The CCD camera will be helpful for this. It won't be perfect, but the better job you do on this coarse alignment, the easier the fine alignment will be.

- **Alignment Hint:** Slide the mount back and forth to center the beam on the first iris (closest to the beamsplitter). Adjust the tilt to center the beam on the second iris. Iterate back and forth between these two adjustments.

- Once you've got it reasonably well aligned, screw it to the table.

- Adjust the vertical and horizontal tilt of the **B'** collection optics to perfectly center the beam on the iris closest to the beamsplitter.

- Adjust the vertical and horizontal tilt of the beamsplitter to center the beam on the iris closest to the downconversion crystal.

- Alternate back and forth between the last two steps, always adjusting the collection optics to center the beam on the first iris, and the beamsplitter to center the beam on the second. When the beam is well centered on both irises, you're done.

- **Turn off the alignment laser.**

- Unscrew the **B'**-fiber from the alignment laser, and reconnect it to the fiber leading to the detector.

VI. Measuring $g^{(2)}(0)$ for a Single Photon State

- Make sure that the room lights and the alignment laser are off, and then turn on the detectors. Open the iris diaphragms and unblock the blue pump beam.

- Slowly rotate the waveplate in front of the beamsplitter while monitoring the count rates. You should notice that for some waveplate angles you get lots of **B** and **AB** counts, but almost no **B'** and **AB'** counts. For other angles you get lots of **B'** and **AB'** counts, but almost no **B** and **AB** counts.

- Rotate the waveplate to maximize the **AB** counts. Adjust the tilt on the **B** mount to maximize this coincidence rate.

- Rotate the waveplate to maximize the **AB'** counts. Adjust the tilt on the **B'** mount to maximize this coincidence rate.

- The maximum **AB** and **AB'** count rates should be nearly the same (within 10 or 20%). If this isn't the case, please ask for help.

♦ Q1: When the waveplate is set to 0°, are the **B** or **B'** counts maximized? How far do you have to rotate the waveplate in order to maximize the other count rate? Explain why the count rates change the way they do when the waveplate is rotated.

♦ Q2: The polarizing beamsplitter reflects vertically polarized light, and transmits horizontally polarized light. What polarization is the light emerging from the downconversion crystal?

- Rotate the waveplate to roughly equalize the **AB** and **AB'** count rates.

- Increase **Update Period** to 1s.

You should notice that there are very few **ABB'** threefold coincidences.

- In the pane with the plots, click on the **g(2)(0)** tab. In the pane labeled **g(2) Measurements,** click **Clear Buffer** and get an idea of the average value of $g^{(2)}(0)$.

The $g^{(2)}(0)$ measurements will fluctuate significantly, but hopefully they should always be less than one.

Now you should be ready to take data.

- In the **Data Taking Parameters** pane set **Update Period (Data Run)** to 10s, and **Number of points** to 10. Click the **Take Data** button.

Hopefully you'll find a value of $g^{(2)}(0)$ that is several standard deviations below 1; if you don't, ask for help. Calculate how many standard deviations your value for $g^{(2)}(0)$ is below 1.

- Take several more data sets with different parameters for **Update Period (Data Run)** and **Number of points**. Always take at least 10 points in order to assure reasonable statistics.

Note that while the ideal theoretical prediction for $g^{(2)}(0)$ of a single photon is 0, experimentally you can't achieve this. Try and adjust the experimental parameters so that you get a data set for which the standard deviation of $g^{(2)}(0)$ is several times smaller than the average value of $g^{(2)}(0)$. In other words, try to get a measurement of $g^{(2)}(0)$ which is different from 0 by more than one standard deviation.

- ♦ Q3: Why can't you measure a value of 0 for g⁽²⁾(0)? Ref. [2] will help you answer this question and the next.

- ♦ Q4: When it's done taking data, the computer spits out a value for g⁽²⁾(0) that it calls the "expected" value. What is this? Does your measured value for g⁽²⁾(0) agree with this expected value (to roughly within the error of the measurement)?

VII. Two-Detector Measurement of $g^{(2)}(0)$

When you've completely finished making measurements on the single photon state, you are ready to show that a single beam of your downconversion source is classical.

- Run the "Coincidence.vi". Set **Experimental Setup** to **g(2)(0) 2-det,** and **Update Period** to 1.0s [this plays the role of T in Eq. (3)]. The computer uses the **BB' Coincidence Window (ns)** parameter as Δt in Eq. (3); ask your instructor what value to use for this parameter (again it should be on the order of 5-10 ns, but won't necessarily be the same as you used for 3-detector measurements). In the pane that displays the graphs, choose the **g(2)(0)** tab.

- Adjust the half-wave plate so that the **B** and **B'** counts are about equal.

The $g^{(2)}(0)$ measurements will fluctuate significantly, but hopefully they should always be around one, or greater.

- Click **Clear Buffer** and get an idea of the average value of $g^{(2)}(0)$.

Now you should be ready to take data.

- In the **Data Taking Parameters** pane set **Update Period (Data Run)** to 10s, and **Number of points** to 10. Click the **Take Data** button.

Hopefully you'll find a value of $g^{(2)}(0)$ that is greater than or equal to 1. If you don't, ask for help. Likely you will find that $g^{(2)}(0)$ is equal to 1 within the error of the measurement.

- Take several more data sets with different parameters for **Update Period (Data Run)** and **Number of points**. Always take at least 10 points in order to assure reasonable statistics.

You've just shown that if you condition your measurements on the presence of a photon in the idler beam, you produce a single photon state in the signal beam. This is a highly non-classical state. If you don't condition your measurements, your signal beam behaves classically.

VII. Write-up

Your write-up should include:

- Answers to all questions.

- A table listing your results. For every data run you take I want to see information on parameters you used, and what results you obtained.

- A brief (one to two page) write-up describing what you did in the lab, and summarizing your results. Feel free to comment on the lab as well: what worked, what didn't, and what might be improved.

References:

[1] P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: A new light on single-photon interferences," Europhys. Lett. **1**, 173-179 (1986).

[2] J.J. Thorn, M.S. Neel, V.W. Donato, G.S. Bergreen, R.E. Davies, and M. Beck, "Observing the quantum behavior of light in an undergraduate laboratory." Am. J. Phys **72**, 1210-1219 (2004).

[3] G. Greenstein and A. G. Zajonc, *The Quantum Challenge, Modern Research on the Foundations of Quantum Theory*, 2nd ed. (Jones and Bartlett, Sudbury, MA, 2006) Ch. 2.

Lab 3:
Single Photon Interference

Lab Ticket -- must be finished before you come to lab. Each group turns in one ticket.
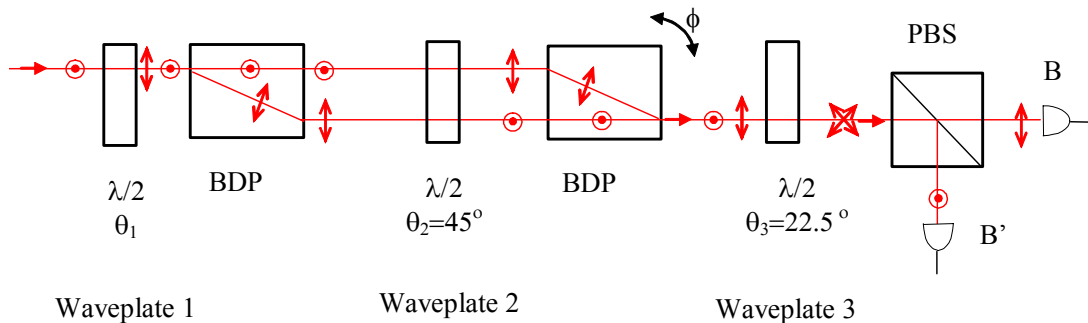
Fig. 1 The polarization interferometer. BDP stands for beam displacing prism (or beam displacing polarizer).

Remember the above interferometer setup from HW? If we measure the number of output photons N_{out} on the B detector in a given time interval, we'll find that in general N_{out} varies sinusoidally with ϕ–we'll see interference. The visibility V of this interference pattern is defined as

$$V = \frac{N_{max} - N_{min}}{N_{max} + N_{min}} \ ,$$

where N_{max} is the maximum number of output counts, and N_{min} is the minimum number. Assuming vertically polarized input photons, calculate the visibility of the measured pattern on detector B as a function of the angle of waveplate 1, θ_1.

Important Safety Tips

- For your safety, **NEVER LOOK DIRECTLY INTO THE LASER.** You should **WEAR THE LASER SAFTY GOGGLES** while in the lab; they will block the intense blue laser light, but still allow you to see.

- **REMOVE YOUR WATCH OR ANY OTHER SHINY JEWLERY THAT'S ON YOUR HANDS OR WRISTS**. A reflection off of a shiny surface can be accidentally directed to someone's eye.

- For the safety of the equipment, **NEVER TURN ON THE ROOM LIGHTS WHILE THE PHOTON COUNTING MODULES ARE ON.**

    There is a small box on the table that has a 3-position switch on it. These boxes are connected to the single photon counting modules (SPCM's). The switch positions are labeled "OFF", "GATE" and "ON" (or just "OFF" and "ON"). **This switch must be in the OFF position when the room lights are on**. There is a separate switch to turn on
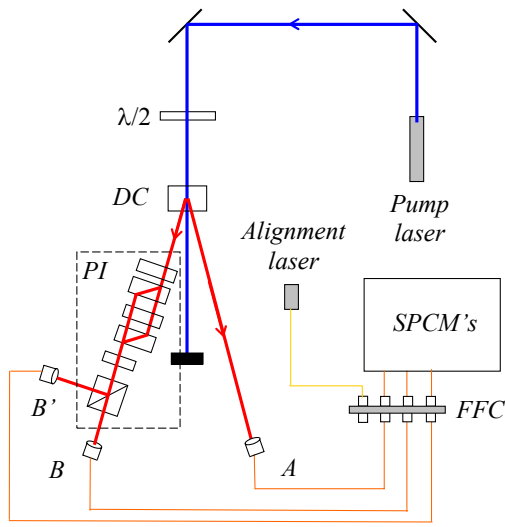
Fig. 2. The experimental apparatus. The polarization interferometer (PI) is in the dashed box.

Fig 3. The BDP's. The large black "knob" on the mount on the right is a stepper motor. It allows the computer to tilt the mount to adjust the phase,

the power to the modules; it is OK for the power to be on, but the detectors themselves must be OFF.

- In general, if the manual is not clear, or you're not completely sure how to do something, **PLEASE ASK FOR HELP**.

I. Introduction

In the last lab, you showed that it was possible to create a beam of true single photons. In this laboratory you will show that if individual photons are passed through an interferometer, they will interfere with themselves. Indeed, it is possible to do both of these experiments at the same time. You will thus be performing an experiment which simultaneously shows both the wave and particle aspects of light.

You'll be using the polarization interferometer we've talked about in class, and that you've worked with in HW and your Lab Ticket, Fig. 1. Since you should be familiar with it, I won't describe how it works here. A diagram of the complete experimental apparatus is shown in Fig. 2, while a picture of the beam displacing prisms is shown in Fig. 3.

Remember, in the last lab we were able to show that the signal beam contained individual photons, as long as we gated everything off the detection of an idler photon. This was done by looking for a lack of coincidences between two detectors monitoring the outputs of a beamsplitter. In Fig. 2, we still have two detectors at the outputs of a beamsplitter, and a gate detector. The only difference is that the beamsplitter is now part of the polarization interferometer.

As far is the output detectors are concerned, the PI is a beamsplitter; it takes one input beam and creates two output beams. The splitting ratio of this "beamsplitter" depends on the phase of

the interferometer [1]. For some phases most of the light is transmitted, while for others most of the light is reflected. We can even adjust the phase so that the beam splits equally.

In the last lab we measured the quantity $g^{(2)}(0)$ with a beamsplitter adjusted for a 50/50 splitting ratio. It turns out that $g^{(2)}(0)$ is independent of the splitting ratio [1]. You can use a 50/50 beamsplitter, or an 80/20 beamsplitter; you will always measure $g^{(2)}(0)$ to be the same. The only caveat is that you can't get too close to 100/0 or 0/100, because then one of the detectors doesn't get much light, both the numerator and denominator of $g^{(2)}(0)$ get small, and experimentally $g^{(2)}(0)$ is not well behaved.
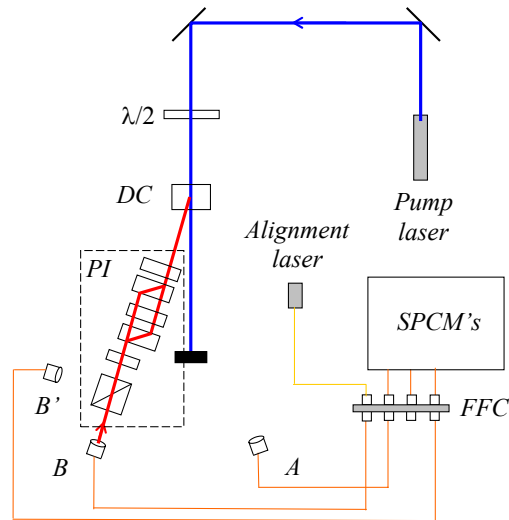

Fig. 4. Observing interference using the alignment laser.

The upshot of all this is that we have all the information we need to measure $g^{(2)}(0)$ at the same time that we measure the interference pattern. It's all the same data, acquired at the same time, but looked at in slightly different manners. You'll be able to see both wave-like behavior (interference), and particle-like behavior ($g^{(2)}(0) < 1$) in the same experiment.

In the previous labs you've done much of the alignment for yourself. Aligning the interferometer is not particularly difficult, but it takes a fair amount of time, especially if you've never done it before. For this reason everything will be aligned when you come into the laboratory. You will use your time in the lab to explore how things like changing the waveplate angles, or blocking one of the interferometer beams, affect the measured interference pattern.

II. Getting Started

- Please wait for me to show you how to turn things on, etc.

- The CCU should be set to measure the following coincidences: Counter 4 - AB; Counter 5 - ABB'; Counter 6 - AB'; Counter 7 - BB'.

- **Make sure the detectors are off and the blue pump beam is blocked.**

- Please don't touch the knobs on the mounts that hold the BDP's. The interferometer is not that sensitive to this alignment, and it's not that hard to realign it, but it's better not to waste time doing so.

- The fiber leading from the **B** collection optics should be connected to the alignment laser, as shown in Fig. 4. If it isn't, connect it now. Turn on the alignment laser (50 mA max) as you were shown previously.

- With the notation that θ_1 is the angle on waveplate 1, etc., make sure that the waveplate angles are set to $\theta_1 = 0°$, $\theta_2 = 45°$, $\theta_3 = 22.5°$.

- Take a piece of white paper or an index card, and carefully insert it in different locations along the beam path so you can see where the beam goes. You'll probably need to have the lights out for this, as the beam is not very bright. You should verify that the beam follows the path shown in Figs. 1 & 4. In particular, you should notice two beams in-between the BDP's.

- While looking at the 2 beams between the BDP's, slowly rotate waveplate 3.

♦ Q1: What happens to the beams as this waveplate is rotated? Explain.

- Rotate waveplate 3 back to $\theta_3 = 22.5°$.

III. Observing Interference

- Insert a polarizer in-between waveplate 1 and the downconversion Crystal; orient it at 45°.

- Insert a sheet of paper so that you can see the beam after it leaves the polarizer. Right now this beam may be very dim and hard to see; don't worry about that for the moment.

- Double-click the "Coincidence.llb" icon on your desktop. This opens a LabView library in a window. Then click on the "Coincidence.vi" icon in the upper left of this window.

- Set **Experimental Setup** to **Interference,** and **Update Period** to 0.2s.

You are using the vi because it has some controls for the stepper motor that scans the interferometer phase. You'll be using it to slowly sweep the phase, so that you can see the interference pattern. When the program is first initialized, the motor is not moving. You should see that the **Pause Stepper** button is grayed ("pushed-in"), and the **Current position (μsteps)** indicator is not changing.

- If the **Current position (μsteps)** indicator does not read 26000, set **Set position** to 26000, and then click the **Goto Set Position** button. The stepper motor should move to this position, and the **Current position (μsteps)** indicator should read 26000.

- Move the **Stepper increment** slider to 4, then click the **Pause Stepper** button to release it. The motor should now be moving, and the **Current position (μsteps)** indicator should be increasing.

- Observe the beam behind the polarizer. You should notice it getting alternately bright and dark as the phase of the interferometer is scanned to produce constructive and destructive interference. If you don't see this, please ask for help.

Note: don't let the stepper motor scan too far -- the interference may go away. You can stop the motor from scanning by clicking the **Pause Stepper** button. Try to keep the stepper motor in the range 25000-27000. To get back to the center of the range, simply set **Set position** to 26000, and then click the **Goto Set Position** button.

♦ Q2: As the motor scans, you should notice that the beam stays bright in front of the polarizer, but gets brighter and darker behind it. Why is this?
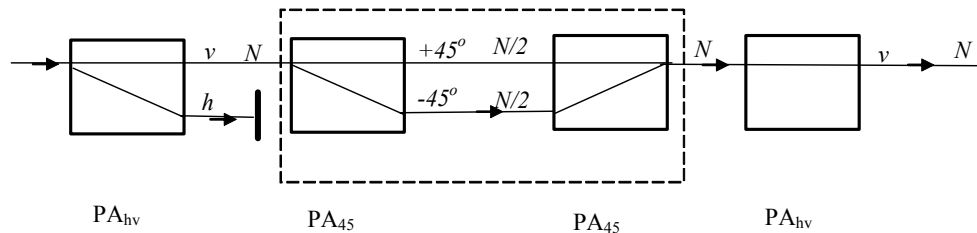
- Pause the stepper motor.

Fig. 5. Experiment 5. The dashed line encloses is what I refer to as an "analyzer loop."

- Remove the sheet of paper and the polarizer, turn off the alignment laser, and reconnect the B-fiber to the B-detector.

IV. Measuring Single Photon Interference

Now we're ready to observe single photon interference.

- **Make sure the lights are out**, then turn on the detectors and unblock the blue beam.

- Set the waveplate angles to $\theta_1 = 22.5°$, $\theta_2 = 45°$, and $\theta_3 = 22.5°$.

- Set **Update Period** to 0.2s, and in the pane with the graphs, click on the **AB & AB'** tab.

- Begin with the stepper motor at 26000, set the **Stepper increment** to 1 or 2, then unpause the stepper and let it scan. Again, don't let it scan too far.

You should see interference fringes in the count rates as the motor scans. The visibility should be fairly high; hopefully it will be 0.9 or better. If the visibility of your fringe pattern isn't very high, please ask for help.

- Set the **Data Taking Parameters** to: **Update Period** (Data Run) 1s, **Number of points** 60, **Center stepper position(μsteps)** 26000, **Range to scan (+)** 150, then click the **Take Data** button to acquire a data set.

Hopefully, your data should have between 2 & 3 full oscillations, and a high visibility. If you don't have between 2 & 3 oscillations, adjust **Range to scan (+)**, then take a new scan.

The singles counts B and B' represent ordinary interference that you'd see with any light source. The coincidence counts AB and AB' represent true single photon interference. This is shown by the fact that your measured values for $g^{(2)}(0)$ should be less than one. At the moment these measurements probably fluctuate greatly; don't worry about this now, we'll come back and clean up the $g^{(2)}(0)$ measurements shortly.

- Take two more data sets, using $\theta_1 = 10°$ and $\theta_1 = 0°$.

♦ Q3: After you leave the lab, calculate the measured visibilities of your interference patterns. Compare them to the prediction made in your lab ticket.

V. Experiment 5

In class you talked about something called Experiment 5. It was drawn as shown in Fig. 5; I suggest you go back and look at your class notes to refresh your mind about the discussion.

In the experiment on your table, you don't need the first polarization analyzer PA_{hv} shown in Fig. 5 because the polarization of the photons produced from your source is already vertical. The analyzer loop, which has no effect on the input polarization, is implemented in your experiment using the BDP's and the 3 waveplates. Remember, you did a HW problem showing that this combination of waveplates and BDP's has no affect on an input polarization, as long as $\theta_3 = \theta_1 + 45°$, and the phase shift is $\phi=\pi$. By rotating θ_1 and θ_3, you can mimic the behavior of rotating the entire analyzer loop of Fig. 5. The final PA_{hv} in Fig. 5 is implemented in your experiment with the polarizing beamsplitter.

- Set the waveplate angles to $\theta_1 = -22.5°$, $\theta_2 = 45°$, and $\theta_3 = 22.5°$.

- While observing the AB and AB' coincidence counts, let the stepper motor run slowly to scan the interferometer phase. When the interferometer output is vertically polarized (AB' maximized and AB minimized) stop the stepper.

Your interferometer is now adjusted so that $\theta_3 = \theta_1 + 45°$, and the phase shift is $\phi=\pi$. It will now behave equivalently to Experiment 5.

- Using the beam block, block the beam in the interferometer that is closest to the edge of the table.

♦ Q4: What do you notice about the AB and AB' coincidence rates? Explain this behavior.

- Unblock the beam closest to the edge of the table, and instead block the other beam.

♦ Q5: What do you notice about the AB and AB' coincidence rates? Explain this behavior.

♦ Q6: With both beams unblocked, what do you notice about the AB and AB' coincidence rates? Explain this behavior.

Remember that when we first discussed this experiment in class, you probably found its results to be counterintuitive.

VI. Particles and Waves

Now it's time to clean up the $g^{(2)}(0)$ measurement.

- Set θ_1 to an angle that you predict will yield an interference pattern with $V \approx 0.9$. (As discussed in the introduction, if the visibility is too high, experimental measurements of $g^{(2)}(0)$ are not well behaved.)

- Take a data run that scans over approximately 2 full oscillations, has at least 30 points, and has an integration time of at least 10s per point.

♦ Q7: What value do you measure for $g^{(2)}(0)$? Be sure to quote your error.

Your coincidence count rates should show a high visibility interference pattern. This shows conclusively that the photons are behaving as waves as they traverse the interferometer. They must take both paths through the interferometer after they leave the first BDP in order to display interference.

Hopefully your measured values of $g^{(2)}(0)$ will all be less than 1, with a mean value that is significantly less than 1. As discussed in detail in the last lab, this shows that the photons are behaving as particles. They can only take one path after they leave the final beamsplitter.

You've done an experiment that unambiguously shows both the wave-like, and the particle-like nature of light.

VII. Write-up

Your write-up should include:

- Answers to all questions.

- Graphs displaying the single photon interference, with varying visibilities, that you observed in Sec. IV. On these graphs make sure that the bottom of the vertical scale starts at 0 -- this makes it easier to see the visibility of the pattern.

- Graphs displaying the single photon interference and the measurements of $g^{(2)}(0)$ you observed in Sec. VI.

- A brief (one to two page) write-up describing what you did in the lab, and summarizing your results. Feel free to comment on the lab as well: what worked, what didn't, and what might be improved.

References:

[1] R. Loudon, *The Quantum Theory of Light*, 3rd ed. (Oxford University Press, Oxford, 2000), pgs 216-222.