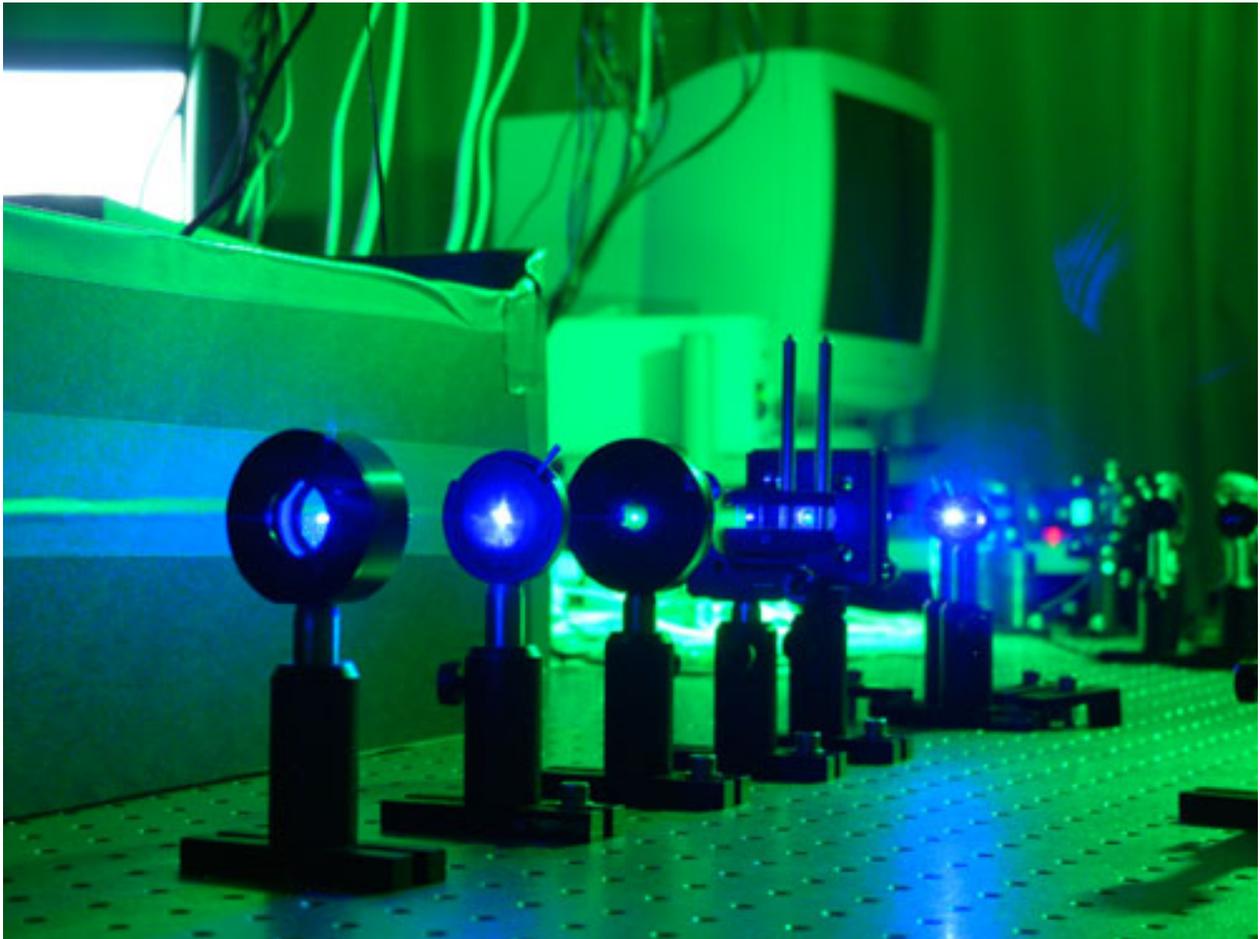


Physics 385L
Quantum Mechanics
Laboratory Manual
Fall 2008



Mark Beck
Whitman College

I'd like to acknowledge the following people, all of whom contributed significantly to the development of these laboratories: Robert Davies, Jeremy Thorn, Matt Neel, Vinsunt Donato, Jeff Bergreen, Ashifi Gogo, Will Snyder, Matt Olmstead, Alex Carlson, Jesse Lord, Dave Branning and Enrique Galvez.

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Laboratory Schedule

<u>Date</u>	<u>Lab</u>	<u>Lab Group</u>
Sept. 4	1	A & B
Sept. 11	1 cont.	A & B
Sept. 18	1	C & D
Sept. 25	1 cont.	C & D
Oct. 2	2	A & B
Oct. 9	2	C & D
Oct. 16	No Lab	
Oct. 23	3	A & B
Oct. 30	3	C & D
Nov. 6	No Lab	
Nov. 13	4	A & B
Nov. 20	4 cont.	A & B
Nov. 27	Thanksgiving	
Dec. 4	4	C & D
Dec. 11	4 cont.	C & D

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 JEWELRY 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.

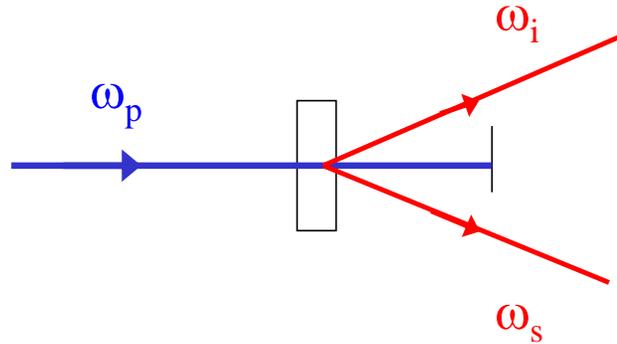


Fig. 1 Spontaneous parametric downconversion.

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

$$\begin{aligned}\hbar\omega_p &= \hbar\omega_s + \hbar\omega_i \\ \omega_p &= \omega_s + \omega_i .\end{aligned}\tag{1}$$

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

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

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{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).

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.

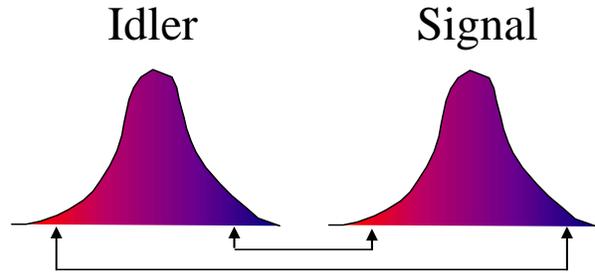


Fig. 2 Correlations between the frequencies of the signal and idler beams. If the idler frequency increases, the signal frequency decreases, and vice versa.

The 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 to 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. 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.

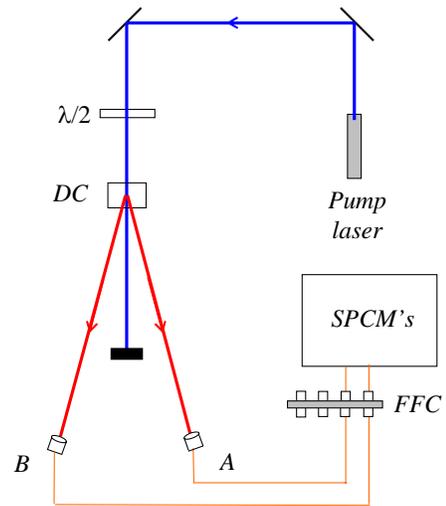


Fig. 3 The experimental arrangement. Here $\lambda/2$ denotes a half-wave plate, DC denotes the downconversion crystal, FFC denotes fiber-to-fiber coupler, and SPCM's denotes the single photon counting modules,

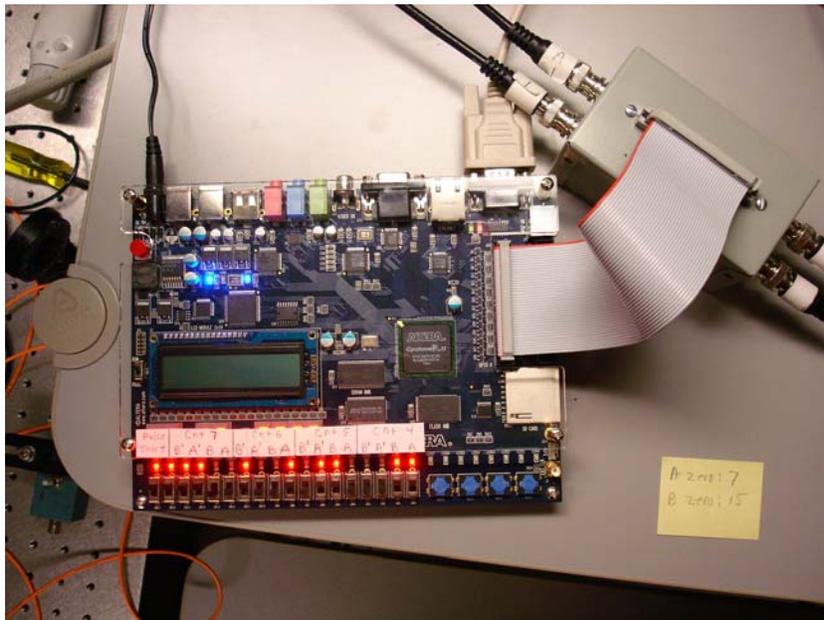


Figure 4: The CCU.



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.

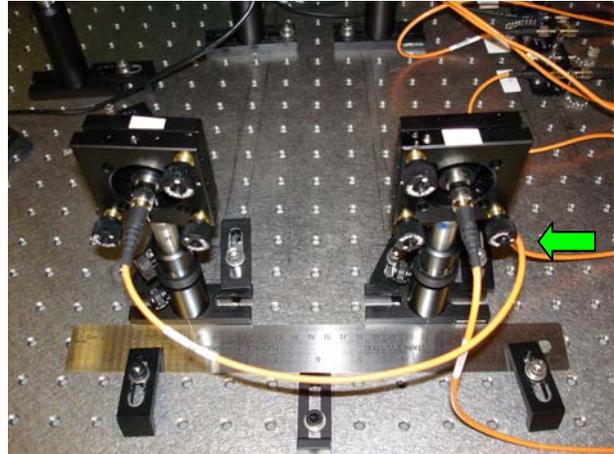


Fig. 6 View from the back side of the mounts, lenses and fibers which collect the downconverted light. The ruler is used to help position things. The green arrow shows the knob you use to adjust the horizontal tilt of the A-detector.

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.

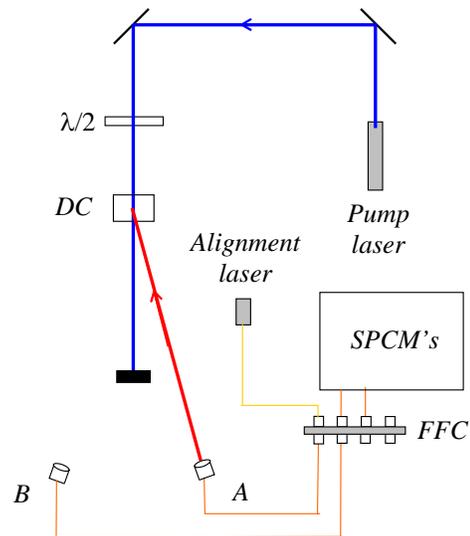


Fig. 7. Using the alignment laser. It should travel backwards from the collection optics, and onto the downconversion crystal.

- 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 lights to be on) and turn on the detectors.

*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 the **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 downconversion 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 JEWELRY 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,

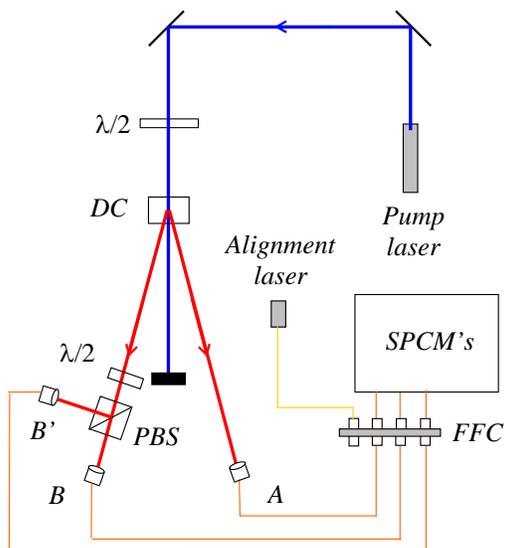


Fig. 1. The experimental apparatus. In addition to the pieces of equipment introduced in the last lab, here we have a polarizing beamsplitter (PBS).

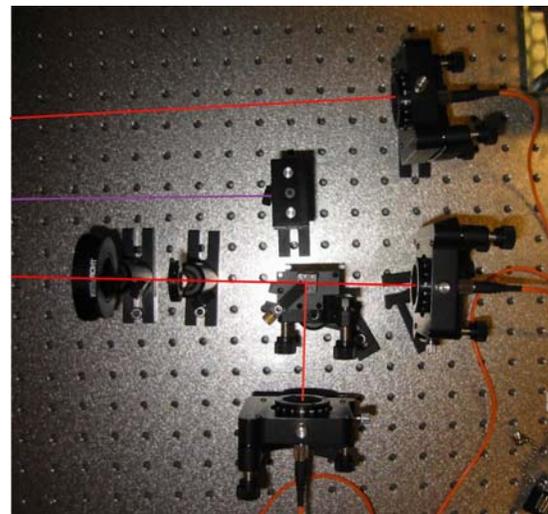


Fig 2. Picture showing the waveplate, PBS, and the collection optics. Beam paths are shown for clarity.

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 $g^{(2)}(0)\geq 1$.

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

$$g^{(2)}(0) = \frac{P_{BB'}}{P_B P_{B'}} \quad (2\text{-detector}), \quad (1)$$

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:

$$P_B = \left(\frac{N_B}{T}\right)\Delta t, \quad P_{B'} = \left(\frac{N_{B'}}{T}\right)\Delta t, \quad P_{BB'} = \left(\frac{N_{BB'}}{T}\right)\Delta t \quad (2)$$

Substituting this into Eq. (1), we get

$$g^{(2)}(0) = \frac{N_{BB'}}{N_B N_{B'}} \left(\frac{T}{\Delta t}\right) \quad (2\text{-detector}). \quad (3)$$

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)]

$$g^{(2)}(0) = \frac{P_{ABB'}}{P_{AB} P_{AB'}} \quad (3\text{-detector}), \quad (4)$$

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:

$$P_{AB} = \frac{N_{AB}}{N_A}, \quad P_{AB'} = \frac{N_{AB'}}{N_A}, \quad P_{ABB'} = \frac{N_{ABB'}}{N_A} \quad (5)$$

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

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

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.**

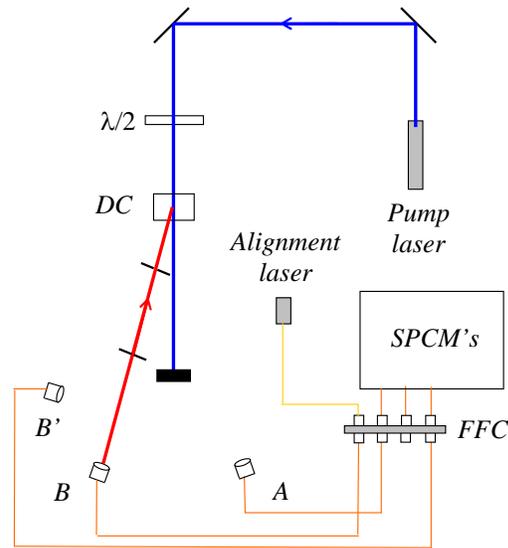


Fig. 3. Using the alignment laser. It should travel backwards from the collection optics, through the irises, and onto the downconversion crystal.

- 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 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.

*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.
- 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.

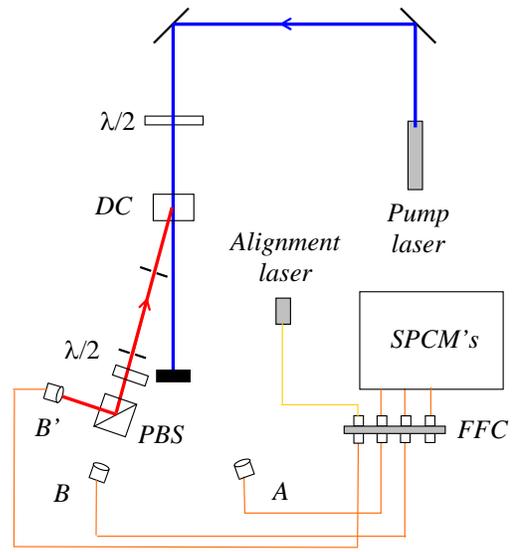


Fig. 4. Aligning the **B'** detector.

- 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-to-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.

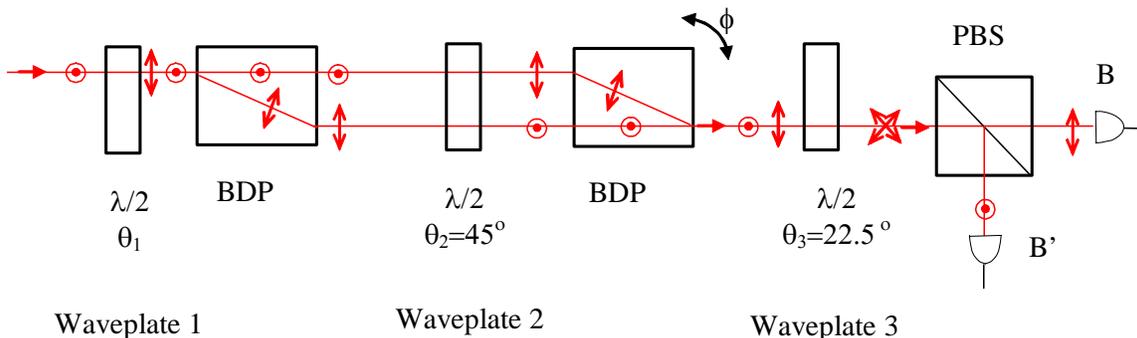


Fig. 1 The polarization interferometer. BDP stands for beam displacing prism (or beam displacing polarizer).

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 SAFETY 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 JEWELRY 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

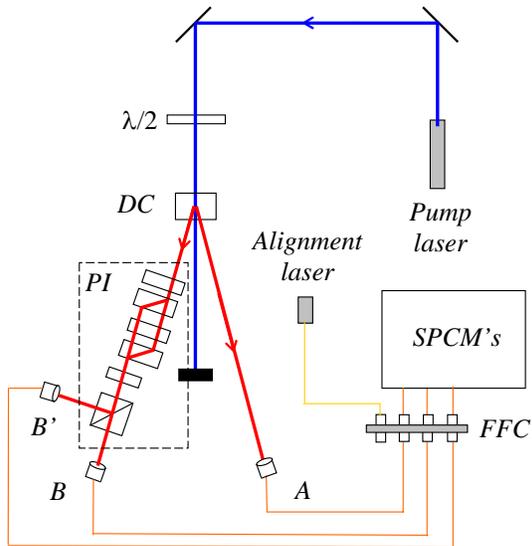


Fig. 2. The experimental apparatus. The polarization interferometer (PI) is in the dashed box.



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 as 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.

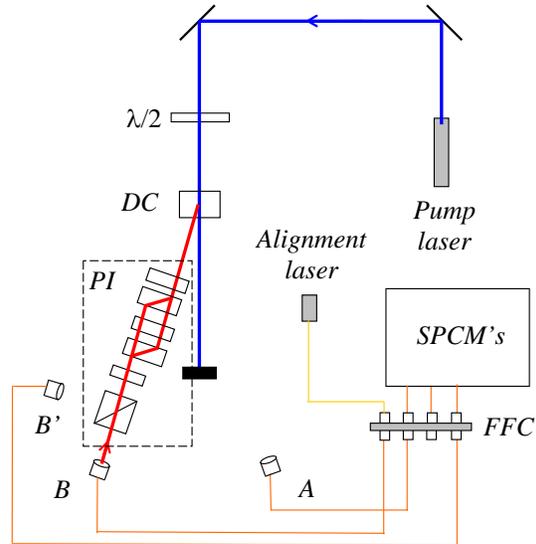


Fig. 4. Observing interference using the alignment laser.

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 $\theta_1 = 0^\circ$, $\theta_2 = 45^\circ$, $\theta_3 = 22.5^\circ$.

- 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 $\theta_3 = 22.5^\circ$.

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 (μ steps)** indicator is not changing.

- If the **Current position (μ steps)** 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 (μ steps)** 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 (μ steps)** 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.

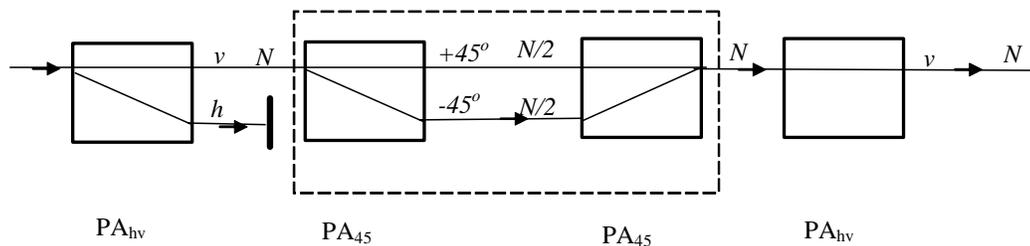


Fig. 5. Experiment 5. The dashed line encloses is what I refer to as an “analyzer loop.”

- 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 $\theta_1 = 22.5^\circ$, $\theta_2 = 45^\circ$, and $\theta_3 = 22.5^\circ$.
- 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**(μ steps) 26000, **Range to scan** (\pm) 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** (\pm), 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 $\theta_1 = 10^\circ$ and $\theta_1 = 0^\circ$.
- ♦ **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 effect on an input polarization, as long as $\theta_3 = \theta_1 + 45^\circ$, 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 $\theta_1 = -22.5^\circ$, $\theta_2 = 45^\circ$, and $\theta_3 = 22.5^\circ$.
- 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 $\theta_3 = \theta_1 + 45^\circ$, 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.

Lab 4:

Testing Local Realism à la Hardy

Lab Ticket -- must be finished before you come to lab.

Create an Excel spreadsheet that calculates $P(-\alpha, \alpha)$, $P(\beta, -\beta)$, $P(\beta, \alpha^\perp)$, $P(-\alpha^\perp, -\beta)$ and H , given the state $|\psi_2\rangle$ in Eq. (4) below. For the fixed value $\alpha = 35^\circ$, make plots of $P(\beta, \alpha^\perp)$, $P(-\alpha^\perp, -\beta)$ and H as functions of β (use values of β between 0° and 90°). How can you maximize H , while still keeping $P(\beta, \alpha^\perp)$, $P(-\alpha^\perp, -\beta)$ less than 0.01? Can you optimize H any further by changing α ? The idea is to always keep $P(-\alpha, \alpha)$, $P(\beta, \alpha^\perp)$ and $P(-\alpha^\perp, -\beta)$ less than 0.01.

You may find it useful to perform a similar exercise using the state $|\psi_1\rangle$ in Eq. (3) below.

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 JEWELRY 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.**

I. Introduction

In this experiment you will be testing local realism. By "local" we mean that measurements performed in one place cannot affect the outcomes of measurements performed somewhere else (assuming that there is no communication between the measurement apparatuses). By "realism" we mean that objects have definite values for measurable quantities, regardless of whether or not we choose to measure them. According to local realism, if two photons are produced by a

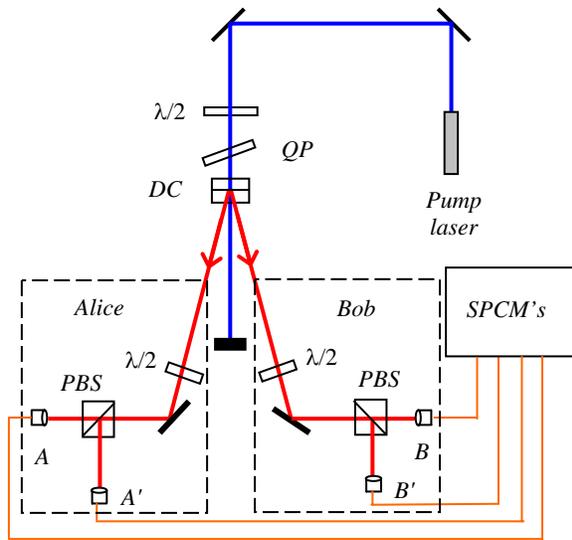


Fig 1 The experimental arrangement. Here QP denotes the quartz plate.

source, their polarizations are completely defined once they leave the source. Thus, polarization measurements performed on one photon cannot affect the results of polarization measurements performed on the other photon.

Local realism is common sense, and all classical systems are bound by it. However, as you will demonstrate in this lab, quantum systems are not constrained by local realism. In order to explain the results of certain experiments we must abandon either locality or reality.

You will be testing local realism using the method suggested by Lucian Hardy that we discussed in class [1-5]. I will not repeat the theory behind this experiment here; you should review your class notes, and read Refs.

[2] & [4] for the details. You will also perform a test that more closely approximates the original test of local realism described by John Bell (Refs. [6] & [7], and references therein).

There is not enough time in the lab for you to totally align the system from scratch. Before you come to lab the detectors will all be aligned. Your job will be to adjust the tuning of the quantum state produced by the source, and to adjust the measurement parameters. Both of these things must be optimized in order to obtain a violation of local realism.

The experimental apparatus is shown in Fig. 1. The downconversion is similar to what we used before, but there's an important difference. There are actually 2 downconversion crystals sandwiched back-to-back, with their crystal axes rotated at 90° with respect to each other. If the downconverted photons are produced in the first crystal, then a horizontally polarized pump photon has become vertically polarized signal and idler photons. If the downconversion occurs in the second crystal, then a vertically polarized pump photon has become horizontally polarized signal and idler photons. To change the ratio of the probability of the production of vertically or horizontally polarized pairs, you change the pump polarization (e.g., if the pump has a larger horizontal component, then vertically polarized outputs are more likely). With this arrangement, the polarizations of the two photons are highly correlated, but any given photon is randomly polarized.

The photons pass through waveplates and polarizers, are focused by lenses into optical fibers, and directed to single photon counting modules (SPCM's) where they are detected. The signal photon travels to Alice and her two detectors (A and A'), while the idler photon travels to Bob and his two detectors (B and B'). We are interested in events where Alice and Bob detect photons at the same time, and the raw data collected in the experiment consists of measuring the number of coincidence counts in a given time window (N_{AB} is the number of coincidences between detectors A and B' in a 1 second counting window, for example.)

Given the four measurements of coincidence counts (N_{AB} , $N_{A'B}$, $N_{AB'}$ and $N_{A'B'}$) we can determine the probability that Alice's and Bob's photons had a particular set of polarizations. The probability that Alice measures her photon to be polarized along the angle θ_A and Bob

measures his photon to be polarized along the angle θ_B is $P(\theta_A, \theta_B)$ —the first variable always refers to Alice’s polarization.

We are interested in probabilities of joint polarization measurements at 4 combinations of angles, determined by two parameters, α and β : $P(-\alpha, \alpha)$, $P(\beta, -\beta)$, $P(\beta, \alpha^\perp)$ and $P(-\alpha^\perp, -\beta)$. The superscript \perp refers to the perpendicular direction, e.g. $\alpha^\perp = \alpha \pm 90^\circ$. Given these 4 probabilities we compute the quantity

$$H = P(\beta, -\beta) - P(\beta, \alpha^\perp) - P(-\alpha^\perp, -\beta) - P(-\alpha, \alpha) . \quad (1)$$

As described in Ref. [4], if $H \leq 0$ the data is consistent with local realism, while if $H > 0$ local realism is violated and we are forced to abandon some of our classical ideas.

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 - A'B; Counter 6 - AB'; Counter 7 - A'B'.
- Double-click the “Angle_scan.llb” icon on your desktop. This opens a LabView library in a window. Then click on the “Angle_scan.vi” icon in the upper left of this window.

Documentation on the program is given in Appendix E. It starts by initializing the counters and the motors which control the waveplate rotation stages; this takes a few seconds and the **Status** indicator reads “Initializing”. Once everything initializes the **Status** should switch to “Reading Counters”. The program is now reading the counters, and updating the screen in real time.

- Make sure that **Update Period** is set to somewhere between 0.2s and 1s. Set the **Subtract Accidentals?** switch to **Yes**; check with your instructor about what coincidence time resolutions you should use.

As you learned in the previous labs, there are always some background “accidental” coincidences that are detected, even when you don’t expect to get any. This is due to the randomness of the photon emission process. By knowing the count rates and coincidence time resolution, we can calculate how many accidental coincidences we would expect to get, and subtract these accidentals from the raw count rates to correct the data. For now we’ll subtract them, but later you can explore what happens if you don’t do this.

When the program is done initializing, the A and B waveplates are set to zero (double check that the **A Position** and **B Position** parameters read 0). With these waveplates settings the A and B detectors monitor horizontally polarized photons from the source, and the A’ and B’ detectors monitor vertically polarized photons from the source.

In your reading of Ref. [4] you learned that the state produced in the downconversion crystals is

$$|\psi\rangle = a|H\rangle_A |H\rangle_B + be^{i\phi}|V\rangle_A |V\rangle_B , \quad (2)$$

where the parameters a , b and ϕ are determined by the settings of the half-wave plate and the quartz plate in the pump beam.

Given that the source produces photons in the state $|\psi\rangle$, and the waveplate axes are set to 0° , you should notice that there are AB coincidences and A'B' coincidences, but essentially no A'B or AB' coincidences (there are always a few due to experimental imperfections).

- ◆ **Q1: Why is this? Calculate the probability of an A'B or AB' coincidence given the state in Eq (2).**

[If you do notice significant A'B or AB' coincidences, it means that the A and/or B waveplates are not properly zeroed. Enter 0 for the **A Desired Position** and the **B Desired Position** parameters, then push the **Move Motors** button. If this does not fix the problem, ask for assistance.]

- Rotate the waveplate in the pump beam by about 10° , then wait a few seconds for the computer to catch up with readings at this new setting.

Notice that no matter how you set the polarization of the pump beam, you can change the ratio of the AB & A'B' coincidences, but never produce any significant A'B or AB' coincidences.

- Adjust the waveplate in the pump beam so that the AB & A'B' coincidence rates are roughly the same.
- Enter 0 for the **A Desired Position** and 45 for the **B Desired Position** parameters, then push the **Move Motors** button.

- ◆ **Q2: What happens to the coincidence rates? Explain this.**

III. Exploring Quantum Correlations--Superposition States and Mixed States

Before you actually try to test local realism, you'll first explore some of the interesting correlations that allow quantum mechanics to violate it.

- Set the A & B waveplates to 0° . Adjust the pump waveplate so that the ratio of the AB & A'B' coincidences is roughly 1:1.

You may want to adjust the **Update Period**. If it is too short the counts will fluctuate a lot, and it will be difficult to get a good reading. If it is too long you need to adjust things very slowly, and wait for the screen to catch up. Values between 0.2 and 1.0 s should work, depending on your count rates. You'll also need to adjust the full scale reading on your meters.

- Now set the A & B waveplates to 22.5° . Adjust the tilt of the quartz plate in the pump beam to minimize the A'B & AB' coincidences. You won't be able to get these coincidences to be as low as with the waveplates set to zero, but you should be able to get them fairly low.
- Iterate back-and-forth between the last two steps. With the A & B waveplates set to 0° adjust the ratio of the coincidences using the pump waveplate; with the waveplates set to 22.5° minimize the A'B & AB' coincidences with the tilt of the quartz plate. You should notice that even with the waveplates set to 22.5° , the ratio of the AB & A'B' coincidences is roughly 1:1.

Stop for a minute and think about what you've done. With the waveplates set to 0° , detectors A & B are measuring horizontally polarized photons from the source, and detectors A' & B' are measuring vertically polarized photons from the source.

- ◆ Q3: If the AB & A'B' coincidences are equal, what do we know about the parameters a and b in Eq. (2)? Do we know anything yet about the parameter ϕ ? Write down the state produced by the source, assuming ϕ to be unknown.

Measurements with the waveplates set to 0° determine the parameters a and b , but not ϕ . In order to determine ϕ , you need to use the results of your measurements with the waveplates set to 22.5° .

- ◆ Q4: Given the state you wrote down in the last question, what must ϕ be in order to explain the fact that the probability of an A'B (or an AB') coincidence is 0 with the waveplates set to 22.5° ? (Ignore your experimental inability to make this coincidence rate perfectly 0.) Write down the state produced by the source.
- ◆ Q5: Given the state you just determined, calculate the joint probability $P(\theta_A, \theta_B)$ that Alice will measure photon A to be polarized along θ_A and Bob will find his photon polarized along θ_B . You might want to refer to a recent HW.

Now you're ready to scan one of the waveplate angles, and measure the joint probability $P(\theta_A, \theta_B)$. The program is designed to fix θ_A and scan θ_B over a present range of angles. **NOTE: the computer scans (and records in a datafile) a waveplate angle, whereas when we talk about $P(\theta_A, \theta_B)$, the angles θ_A and θ_B refer to the angles of a polarizer. Remember that polarizer angles are twice the waveplate angles.**

- In the **Data Taking Parameters** section, set **A** to 0 (this is the fixed waveplate angle), then take a scan with 5 samples per point with counting times of 3–5 s per sample. This data file will automatically be saved. Note that the computer acquires data at 17 values of θ_B between 0° and 90° .
- Repeat this experiment with **Angle A** set to 22.5° (corresponding to a polarizer angle of 45°).

In your report I want to see two graphs. The first is theory and experiment for $P(\theta_A = 0, \theta_B)$, and the second for $P(\theta_A = 45^\circ, \theta_B)$. Plot the theory as a solid line and the data as points. For the theory curves, use the probabilities you obtained in Q5.

In class you talked about the difference between a superposition state and a mixed state. Equation (2) assumes a superposition state—i.e., that at any given time the photon is in both the $|H\rangle_A |H\rangle_B$ and $|V\rangle_A |V\rangle_B$ states. Is this assumption correct? Can we explain our data instead assuming that the photons are in a classical mixture of either the $|H\rangle_A |H\rangle_B$ or $|V\rangle_A |V\rangle_B$ states?

- ◆ Q6: Calculate the probability $P(\theta_A, \theta_B | HH)$ -- the joint probability that Alice will measure her photon to be polarized along θ_A and Bob will find his photon polarized along θ_B , assuming that the photons are in the state $|H\rangle_A |H\rangle_B$.

- ◆ Q7: Calculate the probability $P(\theta_A, \theta_B | VV)$.
- ◆ Q8: If you refer back to the class notes where we talked about mixed states, you'll see that the probability of joint polarization measurements in a mixed state is

$$P_{mix}(\theta_A, \theta_B) = P(\theta_A, \theta_B | HH)P(HH) + P(\theta_A, \theta_B | VV)P(VV),$$

where $P(HH)$ is the probability that the photons are in the state $|H\rangle_A |H\rangle_B$, and similarly for $P(VV)$. These probabilities are both 1/2 here. Calculate $P_{mix}(\theta_A, \theta_B)$.

On your two graphs of $P(\theta_A, \theta_B)$, add graphs of $P_{mix}(\theta_A, \theta_B)$, for appropriate values of θ_A . Plot $P_{mix}(\theta_A, \theta_B)$ as a dashed line.

- ◆ Q9: Is it possible to explain your experimental data using this mixed state? If not with this mixed state, can you think of any mixed state that will agree with both of your data sets? By this I mean, are there any $P(HH)$ & $P(VV)$ that will allow $P_{mix}(\theta_A, \theta_B)$ to agree with both data sets?

Remember, if the data are consistent with a superposition state, we must conclude that the system is in *2 states at the same time*.

IV. Testing a Bell Inequality

The state you've created is the ideal state to test a version of the original Bell inequality (as formulated by Clauser, Horne and coworkers). I won't go into details about this particular test as there are lots of details in our textbook, as well as in the papers by Dehlinger and Mitchell [6, 7]. Suffice it to say that for a particular quantity S , the predictions of local realism are that $|S| \leq 2$.

For the state you've created the quantum prediction is $S = 2\sqrt{2}$, which clearly violates local realism. The quantity S is a sum of four expectation values E ; these expectation values are each measured at a particular set of angles.

- Double-clicking the "Hardy-Bell.llb" icon on your desktop and then running "Hardy-Bell.vi". Documentation on the program is given in Appendix B.
- Set the **Experimental Setup** dial to **S**, and **Update Period** to something between 0.2 and 1.0s. Set the **Subtract Accidentals?** switch to **Yes**.
- Double check that the AB and A'B' coincidences are roughly equal, and that they are maximized and the A'B and AB' coincidences are minimized. This should be true with both waveplates at 0° and at 22.5° . A good figure of merit for this is the "E-meter"—the big blue bar on the right; $E=1$ if A'B and AB' are 0. Your goal is to increase E at both waveplates settings.
- In the **Data Taking Parameters** box set **Update Period (Data Run)** to 10.0s, and **No. Of Samples** to 5, then push the **Take Data** button.

Control of the computer is now switched to the data acquisition program. This program requires nothing from you, it automatically adjusts the waveplates to the correct angles, makes

readings, calculates probabilities and S , and saves the data to a file. For the parameters you just entered the data run will take approximately 4 min. There is no graceful way to exit this program while it is still running, and if you exit in the middle by closing the window, chances are you'll need to reboot the computer--better to just let it run.

- The program is done running when the **Operation** box reads "Finished." The data file is automatically named according to the date and time. In your notebook record the filename, important parameters (Update Period, number of samples), and results (S , errors, etc.). The violations parameter gives the number of standard deviations that your result violates local realism.

Try and get a result that violates local realism by at least 10 standard deviations. If your value for S is greater than 2 but you don't have a 10 standard deviation violation take more than 10s per point (and possibly more points) to decrease the error. If $S < 2$ you probably need to tweak the state with the pump waveplate and quartz plate.

V. Measuring H

Now let's do an experiment where you perform the Hardy test that we described in class.

As discussed above, you'll be measuring the quantity H , which depends on several probabilities, all determined by the parameters α and β . From your reading of Ref. [4] you'll remember that maximum violation of local reality can be achieved using either of the states

$$|\psi_1\rangle = \sqrt{0.8}|H\rangle_A |H\rangle_B + \sqrt{0.2}|V\rangle_A |V\rangle_B . \quad (3)$$

$$|\psi_2\rangle = \sqrt{0.2}|H\rangle_A |H\rangle_B + \sqrt{0.8}|V\rangle_A |V\rangle_B . \quad (4)$$

We'll start with $|\psi_2\rangle$, for which the angle parameters are $\alpha = 35^\circ$ and $\beta = 19^\circ$. Of course, experimentally it is difficult to produce exactly the state $|\psi_2\rangle$, so optimal violation may occur for slightly different values of α and β . We'll begin by attempting to produce state $|\psi_2\rangle$, and assuming $\alpha = 35^\circ$ and $\beta = 19^\circ$.

The magnitudes of the two contributions of the states in Eq. (4) are set by monitoring the probabilities with the half-wave plate set at 0° . Their relative phase is adjusted by attempting to ensure that $P(-\alpha, \alpha) = 0$. You'll notice that in the lower right hand portion of the screen the half waveplate **H (HWP) Measurement Angles** are displayed; these are determined from the **Alpha** and **Beta** parameters entered on the left of the screen (remember that the polarization rotates through an angle 2θ when the waveplate rotates by θ).

- Make sure the **Experimental Setup** dial is set to **H**, and that **Update Period** is set to between 0.2 and 1.0s. Set the **Subtract Accidentals?** switch to **Yes**.
- Make sure that **Alpha** is set to 35° and **Beta** is set to 19° .
- Set the A & B waveplates to 0° . Adjust the pump waveplate so that the ratio of the AB & A'B' coincidences is roughly 1:4. This is most easily done by watching the **P Meter**, which reads the probability of an AB coincidence. You would like it to read 0.2.

- Set the waveplates so that you are measuring $P(-\alpha, \alpha)$. Adjust the tilt of the quartz plate to minimize this probability.
- Iterate back-and-forth between the last two steps. With the A & B waveplates set to 0° adjust the ratio of the coincidences using the pump waveplate; with the waveplates set to measure $P(-\alpha, \alpha)$, minimize this probability with the tilt of the quartz plate. When you've got everything adjusted fairly well, set **Update Period** to at least 1.0s, to get better statistics.
- Set your waveplates to measure $P(\beta, \alpha^\perp)$ and $P(-\alpha^\perp, -\beta)$. These probabilities should be fairly small. Set your waveplate to measure $P(\beta, -\beta)$; this probability should be larger than the others.

By now the pump waveplate and the quartz plate should be reasonably well adjusted. You're ready to take a data run which measures H .

- In the **Data Taking Parameters** box set **Update Period (Data Run)** to 10.0s, and **No. Of Samples** to 5, then push the **Take Data** button.

Control of the computer is now switched to the data acquisition program. This program requires nothing from you, it automatically adjusts the waveplates to the correct angles, makes readings, calculates probabilities and H , and saves the data to a file.

- The program is done running when the **Operation** box reads "Finished." The data file is automatically named according to the date and time. In your notebook record the filename, important parameters (Alpha, Beta, Update Period, angle of the pump waveplate, etc.), and results (H , probabilities, errors, etc.).
- Once you have written down all of these parameters, you can close the window of the data recording program.

VI. Optimizing Your Results

How did your data look? Chances are you measured a value for H that was less than 0; or maybe it was greater than 0, but not by very much (the **Violations** result tells you by how many standard deviations your value of H exceeds 0.) You'd really like to see values of 0.02 or less for the probabilities you expect to be 0, and you'd like to see 10 or more violations. This would be a very convincing result.

You can increase the number of violations you get by either increasing H , or decreasing the error. At the same time, you'd like to make sure that you stay below 0.02 for the probabilities you expect to be 0. For an accurate error measurement you should be using 10 for the **No. of Samples** parameter (we only used 5 for the first data set because we wanted to get a quick run. Your final data runs should always include 10 samples.) Increasing the **No. of Samples** parameter will not decrease the error, it will only make the error measurement more accurate. The only good way to decrease the error of your measurement is to increase the **Update Period (Data Run)** parameter, which increases the time for a data run.

In order to increase H , you need to increase $P(\beta, -\beta)$, while trying to keep all the rest of the probabilities on the order of 0.02. How do you do this? Start by using the results of your Lab

Ticket. Assume the value for α is unchanged, how do you adjust β in order to increase H ? Remember that you need to keep three of your probabilities down around 0.01.

- Rerun the program using a new value for **Beta**.
- Double check the alignment of the pump beam waveplate and the quartz plate. With the A & B waveplates set to 0° adjust the ratio of the coincidences using the pump waveplate; with the waveplates set to measure $P(-\alpha, \alpha)$, minimize this probability with the tilt of the quartz plate.
- Take another data run.

Keep adjusting your parameters and retaking data until you get at least a 10 standard deviation violation of local realism, with 3 of your probabilities as low as reasonably possible (a few percent). This data run needs to use 10 samples.

VI.a. Optimization Hints

Don't stress too much about getting $P(-\alpha, \alpha)$ super low by tweaking the waveplate and the quartz plate--it should be down near 0.02 or 0.03, but it's my experience that this is the most difficult of the probabilities to get very low. I've found that the main parameter to adjust is **Beta**, while adjustments of **Alpha** will help some as well.

Once you've got your value for H up to 0.05 or above, the best way to increase your number of violations is to decrease your error by taking longer data runs with an increased **Update Period (Data Run)**.

I know it can be tedious making small adjustments to parameters and waiting 10 minutes or so for a data run to complete. Having the computer stop running and simply spit out a value for H can be somewhat anti-climactic. However, try not to lose sight of the big picture. Remember the argument that a value of $H > 0$ means that local realism is violated. When you're all done, you'll have proven that classical mechanics doesn't always work!

For all of the above experiments you've been subtracting the accidental coincidences. Once you've gotten a convincing result turn off the accidentals subtraction, but leave everything else the same. How does this affect your results?

VII. Last Experiment

Redo what you've done above using the state $|\psi_1\rangle$ of Eq. (3).

Note that this is a different state, so it will require different values for α and β . Remember: don't just change α and β --**you have to adjust the pump waveplate and the quartz plate to change the state.**

- ♦ Q10: With this state, what values of α and β will yield 0 for $P(-\alpha, \alpha)$, $P(\beta, \alpha^\perp)$ and $P(-\alpha^\perp, -\beta)$? Start by finding the value for α by looking at $P(-\alpha, \alpha)$, then find β .

You should be certain to answer this question before you come to lab on the second day.

VIII. Write-up

Your write-up should include:

- Answers to all questions.
- Graphs from measurements in Sec. III.
- A table listing your results. For **every** data run you take I want to see information on your parameters: S or H measurement, **Alpha**, **Beta**, **Update Period**, whether or not accidentals were subtracted, etc. I also want to see your results: H , error, probabilities, etc.. Please include comments for the data runs, noting if you made adjustments to the waveplate, etc.
- A brief (one to two page) write-up describing what you did in the lab, and summarizing your results. Discuss issues such as how H changed as you adjusted the various parameters, and whether these were the changes that you expected. Feel free to comment on the lab as well, what worked, what didn't, and what might be improved.

References

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- [5] A. G. White, D. F. V. James, P. H. Eberhard, and P. G. Kwiat, "Nonmaximally entangled states: Production, characterization, and utilization," *Phys. Rev. Lett.* **83**, 3103 (1999).
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Documentation for LabView vi's for QM Experiments

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These vi's were all specifically written to read data from the DE2 coincidence counting unit. Data streams from the DE2 counter at a rate of 10Hz over an RS-232 (COM) serial port.

Brief descriptions of the vi's:

Appendix A -- Coincidence_rs232.vi

Used to acquire data for several experiments: coincidence measurements, proving the existence of photons [$g^{(2)}(0)$ measurements], and single photon interference.

Appendix B – Hardy_Bell_rs232.vi

Used to acquire data for Hardy's test of local realism, or a Bell (CHSH) inequality test.

Appendix C - MCA.vi

Used to mimic the behavior of a multichannel analyzer (MCA) using an analog-to-digital converter; it saves you the money of buying a dedicated MCA. This is useful for measuring the arrival time of photons using a TAC.

Appendix D – Coincidence_time_res_rs232.vi

Used to calibrate the coincidence time resolution.

Appendix E – Angle_scan_rs232.vi

Used to examine two photon polarization correlations (joint probabilities) as a function of angle.

Appendix A – Coincidence_rs232.vi

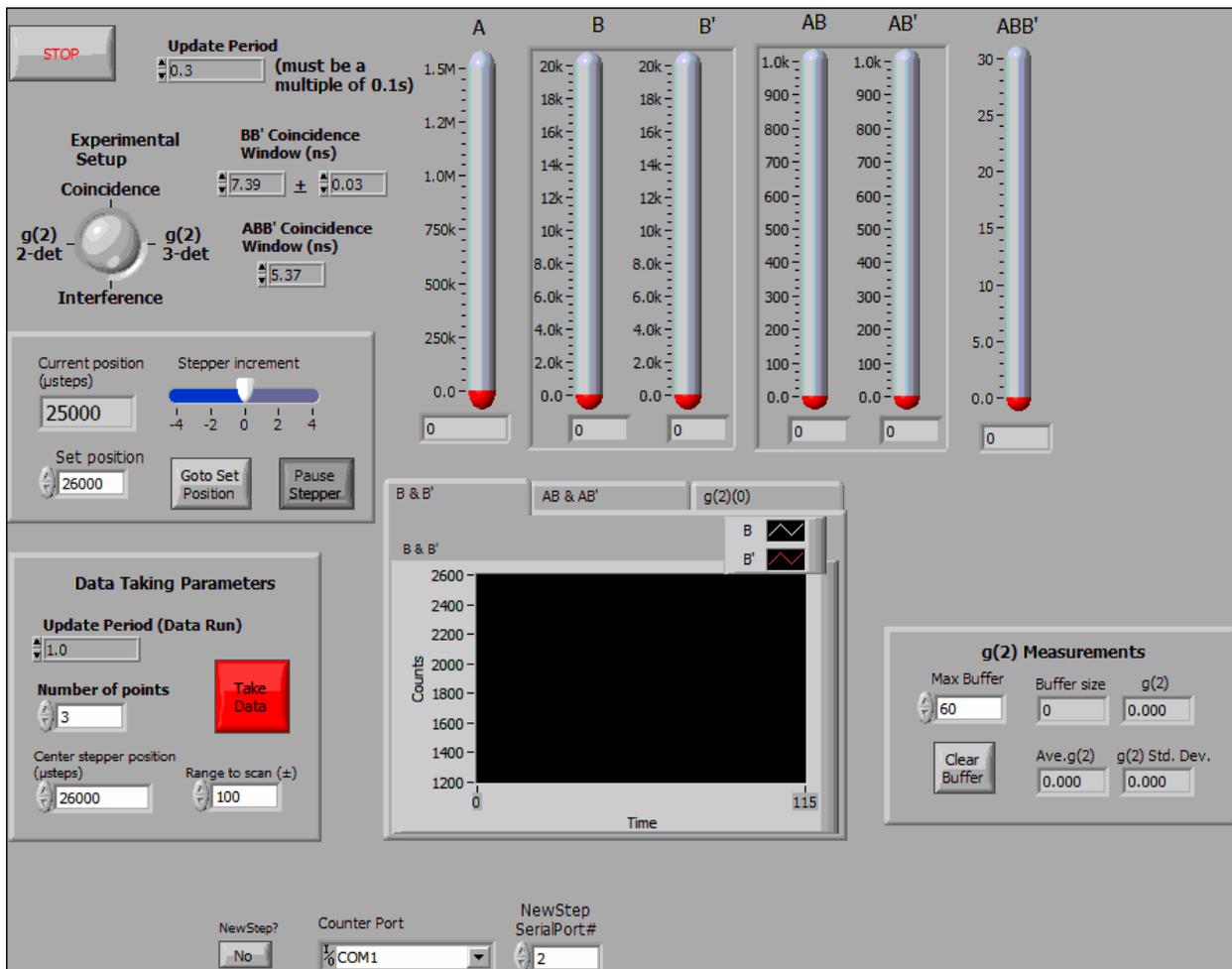
This appendix describes the LabView vi used to acquire data for several experiments: coincidence measurements, proving the existence of photons, and single photon interference.

I. Starting Out

The appearance of this vi will change depending on the experiment you are doing (as determined by the **Experimental Setup** knob on the vi.) The experiment with the most controls and indicators is the interference experiment, and the front panel for this experiment is shown below. If you are doing a different experiment, some of the objects may not be visible.

Coincidence_rs232.vi

Front Panel



Description

This is the program you use to run one of 4 different experiments:

- 1) Simply measuring coincidences between two beams.
- 2) Measuring $g(2)(0)$ for 2-beams using 3-detectors.
- 3) Measuring single photon interference patterns (and simultaneously $g(2)(0)$ for 2-beams using 3-detectors).
- 4) Measuring $g(2)(0)$ for 1-beam using 2-detectors.

Note that $g(2)$ is calculated differently depending on whether you're making 3-detector or 2-detector measurements. See details in the description of the "g(2) Measurements" parameter.

This vi was specifically written for the Altera DE2 counter. Data streams to the computer from the DE2 over the RS232 serial port.

The program does not record data to a file right away, but displays the counters in real time so that you can align things.

Once everything is aligned and the parameters are set, you press the "Take Data" button. This transfers control to another program which records a data set and saves it to a file.

Note that there is one control: "NewStep?" that tells the computer what hardware you have present in your experiment. This control is not visible normally. It located below the "Data Taking Parameters", so you'll need to scroll the window down to access it. This control is only read once at the beginning of execution--so it must be properly set BEFORE you run the program.

The "NewStep?" control tells the computer whether or not you have a NewStep stepper motor attached to your computer to control phase adjustments of the interferometer. This control is useful so that the computer won't try to communicate with an instrument you don't have, causing a hang-up. By default "NewStep?" is set to "No"--if you do have a NewStep, you'll want to change the default to "Yes". For more info see the description of this control below.

For interference measurements, a Newport NewStep actuator (inexpensive stepper motor) is used to tilt a beam displacing polarizer to adjust the phase of a polarization interferometer. This actuator is controlled by a NewStep controller, connected to a serial port of the computer with an RS-485 to RS-232 converter. If you do not have this controller, set the "NewStep?" parameter to "No".

Signals that should be selected on the DE2 for the coincidence counters:

A (Counter 0)

B (Counter 1)

A' (Counter 2) – unused by this vi

B' (Counter 3)

AB (Counter 4)

ABB' (Counter 5) – used for 3-detector $g(2)$ measurements (and interference)

AB' (Counter 6)

BB' (Counter 7) – used for 2-detector $g(2)$ measurements

Note that for the coincidence experiment, only 3 counters are used: A, B, and AB. For the other 3 experiments, 7 counters are used.

On startup, the program initializes the counters.

After initialization the program simply loops and displays the counts in a given time window (determined by the "Update Period" control in the upper left.) This is useful for tweaking the alignment and adjusting parameters.

Nothing is written to disk until the parameters are chosen and the "Take Data" button is pressed. This loads a second VI that records and saves data to disk. Parameters for this data acquisition phase are set in the "Data Taking Parameters" box.

When performing an interference experiment, the stepper motor will automatically adjust the tilt of the beam displacing prism, changing the phase.

Help for each of the controls and indicators can be obtained from the Contextual Help window <ctrl - H> by mousing over each control or indicator. Full documentation for each control and indicator can be obtained by printing using: File>Print>Custom, and then checking "All controls" and "Descriptions".

Controls and Indicators

Coincidence Measurements



Experimental Setup

Which measurement to perform.

Coincidence: Measures A, B, and AB counts.

g(2) 3-det: Make g(2) measurements on 2 correlated beams using 3-detectors. This is the single photon measurement.

Interference: interference measurement [with simultaneous g(2) 3-detector measurement]

g(2) 2-det: Make g(2) measurements on a single beam using 2-detectors. This is the classical field measurement.



Stop

Use this to stop. If you stop some other way you'll probably need to quit LabView and restart; you may even need to reboot the computer.



Update Period

[Must be a multiple of 0.1s]

Time window (in s) for the counters during setup phase (i.e., before the "Take Data" button is pressed.) Readings update once each time window if "Status" reads "Reading Counters".



Counts A, B, B'

Singles counts in the time window specified by "Update Period" (upper left)



Counts AB, AB'

Coincidence counts in the time window specified by "Update Period" (upper left)



Charts

Click on the tabs to display running plots of different measurements: **B & B'**, **AB & AB'**, or **g(2)**.



Update Period (Data Run) [Data Taking Parameter]

[Must be a multiple of 0.1s]

Time window (in s) for counters during data acquisition.

This applies after the "Take Data" button has been pressed.



Number of points [Data Taking Parameter]

Number of measurements that are made during data acquisition.

Error measurements are essentially useless if this is less than 5. 10 is a better minimum number. For interference measurements, you will want to use many more than this so you can better see the pattern.



Take Data [Data Taking Parameter]

Leave the setup "tweaking" mode and switch to data acquisition mode.



NewStep?

Is the NewStep controller present?

If No, there is no attempt to communicate with the NewStep controller. Useful if you don't have a NewStep controller. In this case, the "Interference" experiment is unavailable. If you set "Experimental Setup" to "Interference", the program will act as though it's set to "g(2) 3-det".

If Yes, the NewStep functions normally.

This parameter is only read once, when the vi first starts to run. Therefore, it needs to be set BEFORE you run the program.



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.



NewStep SerialPort#

Number of the serial (COM) port that the NewStep controller is connected to.

3-Detector g(2) Measurements

All of the above parameters apply, plus the following:



ABB' Coincidence window

Coincidence window for ABB' measurements.

Used to determine expected g(2) for 3-detector (single-photon) measurements. Basically, this parameter determines the number of expected accidental ABB' counts.



Counts ABB'

Three-fold coincidence counts in the time window specified by "Update Period" (upper left)



g(2) Measurements

The program calculates g(2) for every loop--and this value is displayed as **g(2)**.

Calculated differently depending on which experiment you're doing.

Formulas:

T: update period (counting window, in S)

dt: BB' coincidence window (in nS)

3-detector, 2-beam experiment:

$$g(2)=(A*ABB')/(AB*AB')$$

2-detector, 1-beam experiment:

$$g(2)=(BB'/(B*B'))*(T/(dt*1.0e-09))$$

These g(2) measurements are then stored in an array, which contains the most recent measurements.

g(2) Ave. and **g(2) Std. Dev** are the mean and standard deviation of these stored measurements.

Max Buffer is the maximum size of this array (i.e., the largest number of measurements that will be averaged).

Buffer size is the current length of the array that is being averaged.

Clear Buffer clears out the array, and new measurements begin repopulating it.

Interference Measurements

Interference measurements assume a 3-detector setup for g(2) calculations.

All of the above parameters apply, plus the following:



Current position (μ steps)

Current position of the stepper motor.

26000 is about the center of the range with the mount we are using.



Stepper increment

Amount that the stepper increments on each loop if the "Pause Stepper" button is off.



Set position

Force the stepper motor to go to this position by pushing the "Goto Set Position" button.

26000 is about the center of the range with the mount we are using.



Go To Set Position

Forces the stepper motor to go to the "Set position".



Pause stepper

If this is in, the stepper motor is stopped. If it is out, the stepper increments by "Stepper increment" on each loop.



Center stepper position (μ steps) [Data Taking Parameter]

Center of the range for the stepper during data acquisition.



Range to scan (\pm) [Data Taking Parameter]

Range for the stepper during data acquisition.

At each point of data acquisition, the stepper moves evenly between ("Center stepper position" - "Range to scan") and ("Center stepper position" + "Range to scan")

2-Detector $g(2)$ Measurements

All of the above parameters apply, plus the following:



BB' Coincidence window

Coincidence window for BB' measurements.

Needed to determine $g(2)$ for 2-detector (classical) measurements.



2D window stdev

Standard deviation of coincidence window for BB' measurements.

Needed to determine the error in $g(2)$ for 2-detector (classical) measurements.



BB' BB' coincidences.

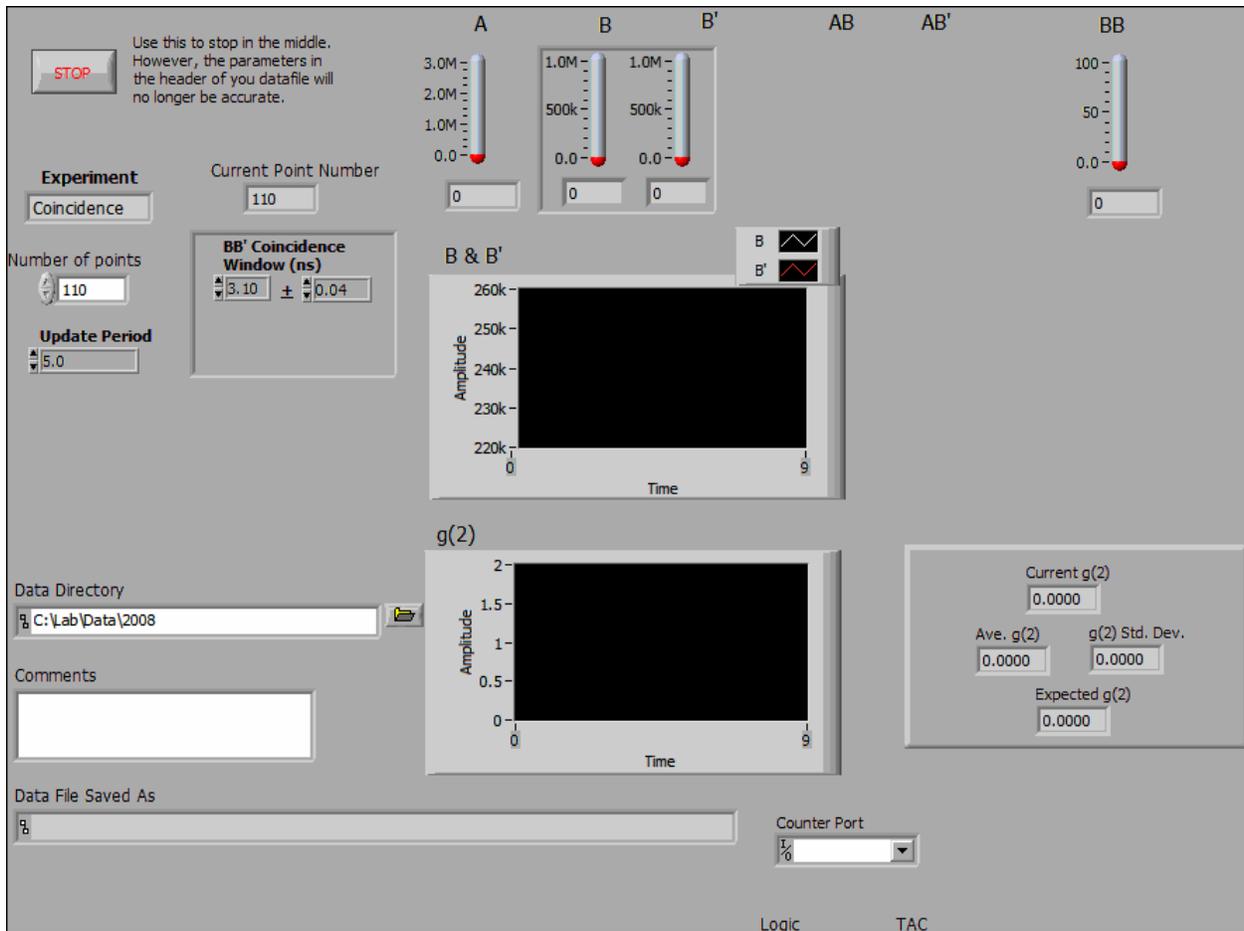
Only used for 2-detector $g(2)$ measurements.

II. Taking Data

When you move to data taking mode, the program you see will look something like that shown below. Again, the appearance of this vi will change depending on the experiment you are doing.

Coincidence_Recorder_rs232.vi

Front Panel



Description

This VI should ONLY be called from the "Coincidence_rs232" VI--necessary parameters are set there.

This program records data (using parameters set in the "Coincidence_rs232.vi") and saves the data to a file.

For a more detailed description of the parameters, see "Coincidence_rs232.vi" .

Controls and Indicators



Stop

Use this to stop in the middle of a data run. However, the parameters in the header of your datafile will no longer be accurate (e.g., you won't have as many points as the header says.)

Also, if you stop some other way you'll probably need to quit LabView and restart; you may even need to reboot the computer.



Experiment

Displays which experiment is being performed: Coincidence, $g(2)$, or Interference.



Number of points

Number of measurements that are made during data acquisition.



Current Point Number

The data point that the computer is currently acquiring.



ABB' Coincidence window

Coincidence window for ABB' measurements.

Used to determine expected $g(2)$ for 3-detector (single-photon) measurements. Basically, this parameter determines the number of expected accidental ABB' counts.



BB' Coincidence window

Coincidence window for BB' measurements.

Needed to determine $g(2)$ for 2-detector (classical) measurements.



BB' 2D window stdev

Standard deviation of coincidence window for BB' measurements.

Needed to determine the error in $g(2)$ for 2-detector (classical) measurements.



Update Period

Time window (in s) for counters during data acquisition.



Data Directory

Path to directory where the data will be saved.



Comments

A space where you can enter comments about the data run. These get saved in the header of the data file.

Once you've entered the text, note that you must hit "Enter" on the NUMERIC KEYPAD, not the "Enter" (or "Return") on the regular keyboard for this text to be saved.



Data File Saved As

Path to the data file. The data file is automatically named using the date and time.



Counts A, B, B'

Singles counts in the time window specified by "Update Period" (upper left)



Counts AB, AB'

Coincidence counts in the time window specified by "Update Period" (upper left)



Counts ABB'

Three-fold coincidence counts in the time window specified by "Update Period" (upper left)



Graphs

Displays graphs of B and AB [Coincidence measurement], or **B & B'**, **AB & AB'**, and **g(2)**. [g(2) and Interference measurement.]



Ave. AB [Coincidence measurement only]

Average value of AB coincidences. Updated when program ends.



AB Std. Dev. [Coincidence measurement only]

Standard deviation of AB coincidences. Updated when program ends.



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.

g(2) Measurements (both 2-Detector and 3-Detector)

All of the above parameters apply (except “Ave. AB” and “AB Std. Dev.”), plus the following:

▶DBL **Current g(2)**

g(2) measurement for the current data point.

▶DBL **Ave. g(2)**

Average of the g(2) measurements.

▶DBL **g(2) Std. Dev.**

For 3-detector measurements this is the standard Deviation of the g(2) measurements.

For 2-detector measurements during data acquisition it is the standard deviation of the g(2) measurements. At the end this error is added in quadrature with the error in g(2) due to the uncertainty of the BB' coincidence time window (“BB' 2D window stdev”).

▶DBL **Expected g(2)**

Calculate the expected value of the parameter $g^{(2)}(0)$. Based on number of expected accidental coincidences.

Calculated differently depending on which experiment you're doing.

For 2-detector, 1-beam measurements, this is assumed to be 1.0 (a classical beam).

For all other measurements, when the vi first starts running it is set to 0.0, and is updated with the expected g(2) at the very end.

Formula (from Appendix A of Thorn AJP)

T: update period (counting window, in S)

dt: ABB' coincidence window (in nS)

$$g(2) = (dt * 1.0e-09 / T) * A * ((B / AB) + (B' / AB'))$$

Interference Measurements

Interference measurements assume a 3-detector setup for $g(2)$ calculations.

All of the above parameters apply (except “Ave. AB” and “AB Std. Dev.”), plus the following:



Starting stepper position

Position of stepper motor at start of scan.



End stepper position

Position of stepper motor at end of scan.

Over the course of a data run, the motor steps evenly between the starting and ending positions.



Current Position

Position of stepper motor for the current data point.

Appendix B – Hardy_Bell_rs232.vi

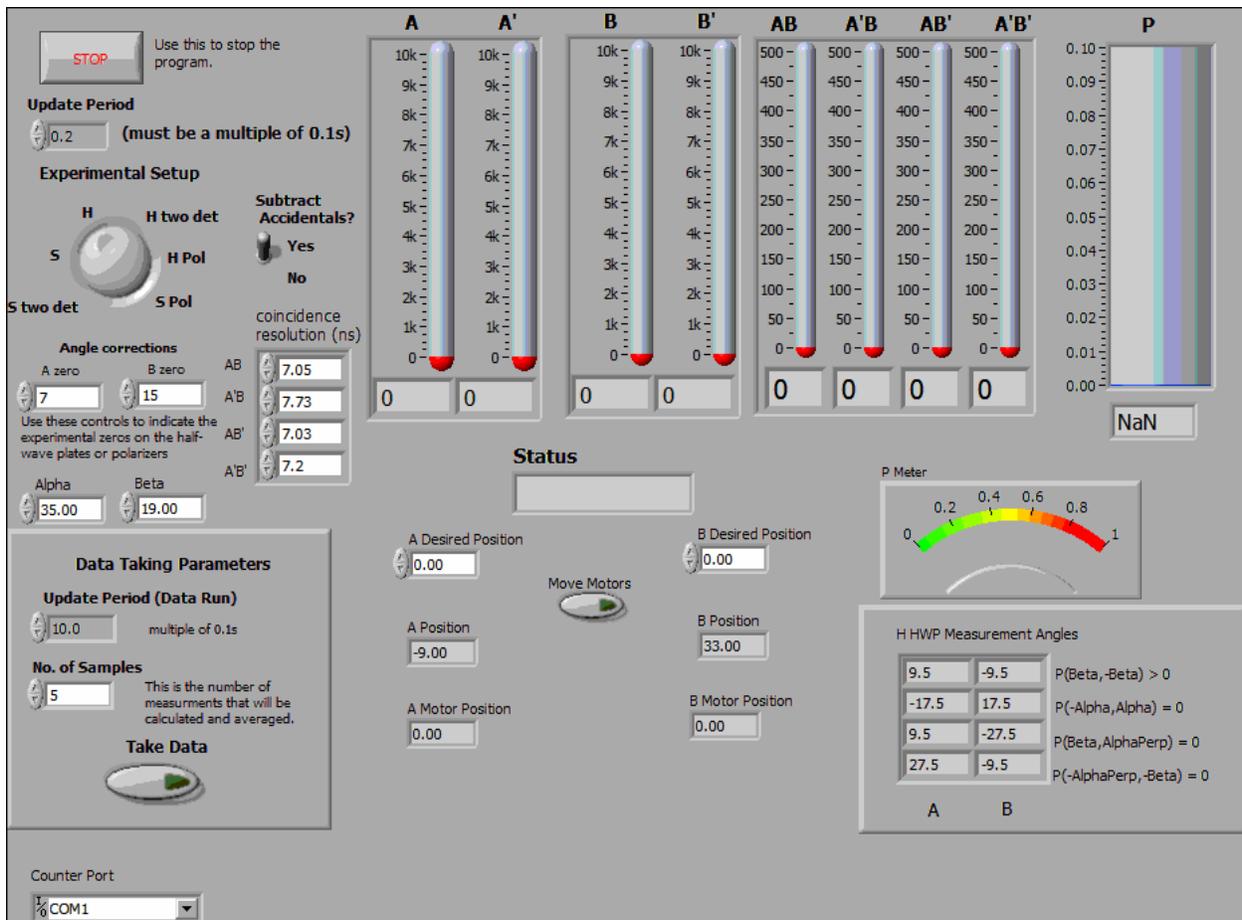
This appendix describes the LabView vi used to acquire data for Hardy’s test of local realism, or a Bell (CHSH) inequality test.

I. Starting Out

When you first run the vi, the program that you see is:

Hardy_Bell_rs232.vi

Front Panel



Description

This is the program you see first when you start to run the experiment. It can be used for either Hardy-type or Bell-type measurements. It does not record data to a file right away, but displays the counters in real time so that you can align things. It also gives you interactive control over such things as the waveplate angles.

Once everything is aligned and the parameters are set, you press the "Take Data" button. This transfers

control to another program which records a data set and saves it to a file.

This vi was specifically written for the Altera DE2 counter. Data streams to the computer from the DE2 over the RS232 serial port.

Waveplates (or polarizers) are controlled by a Newport ESP300 controller at GPIB address 1. On program start, during initialization, the motors home themselves. The motors then set the waveplates to 0 (using the corrections in "A zero" and "B zero").

The DE2 board must be properly set to record the proper coincidences. The coincidences that should be mapped to a given counter are:

A (Counter 0)

B (Counter 1)

A' (Counter 2)

B' (Counter 3)

AB (Counter 4)

A'B (Counter 5)

AB' (Counter 6)

A'B' (Counter 7)

On startup, the program initializes the motors and the counters. During this time the "Status" indicator reads "Initializing".

After initialization the program simply loops and displays the counts in a given time window (determined by the "update Period" control in the upper left.) Status reads "Reading Counters". This is useful for tweaking the alignment and adjusting parameters. Waveplates (or polarizers) are moved by first setting the desired waveplate angles in the " A(B) Desired Position" controls, and then pressing the "Move Motors" button. Status changes to "Moving Motors" while the motors are in motion.

Nothing is written to disk until the parameters are chosen and the "Take Data" button is pressed. This loads a second VI that records and saves data to disk. Parameters for this data acquisition phase are set in the "Data Taking Parameters" box.

During data acquisition the motors will automatically set the waveplates to the correct angles. Angles for a Bell measurement are fixed. Angles for a Hardy measurement are determined from the controls "Alpha" and "Beta".

Help for each of the controls and indicators can be obtained from the Contextual Help window <ctrl - H> by mousing over each control or indicator. Full documentation for each control and indicator can be obtained by printing using: File>Print>Custom, and then checking "All controls" and "Descriptions".

Controls and Indicators



Stop

Use this to stop. If you stop some other way you'll probably need to quit Labview and restart; you may even need to reboot the computer.



Update Period

[Must be a multiple of 0.1s]

Time window (in s) for the counters during setup phase (i.e., before the "Take Data" button is pressed.) Readings update once each time window if "Status" reads "Reading Counters".



Experimental Setup

Which Measurement to perform.

H: Hardy measurement (4 detectors)

H two det: Hardy measurement (2 detectors - waveplates)

H Pol: Hardy measurement (2 detectors - polarizers)

S: Bell measurement (4 detectors)

S two det: Bell measurement (2 detectors - waveplates)

S Pol: Bell measurement (2 detectors - polarizers)



A zero

Motor angle at which A waveplate axis is 0.



B zero

Motor angle at which B waveplate axis is 0.



Alpha (Hardy measurements only)

Angle Alpha used in the Hardy measurement.



Beta (Hardy measurements only)

Angle Beta used in the Hardy measurement.



Subtract Accidentals?

Determines whether or not accidental coincidences are subtracted. Controls data taking mode as well as tweaking mode.



coincidence resolution (ns)

The coincidence time resolutions (used in subtraction of accidentals).



Status

Program Status:

Initializing: initializing the counters and motors.

Reading Counters: Program is looping, reading the counters and updating the screen.

Moving Motors: Waveplates (polarizers) are rotating.



A Desired Position

Angle to set A waveplate to.

Movement occurs after "Move Motors" button is pressed.



B Desired Position

Angle to set B waveplate to.

Movement occurs after "Move Motors" button is pressed.



Move Motors

Set the motors to the "Desired Positions"



A Position

Current angle of the A waveplate.



B Position

Current angle of the B waveplate.



A Motor Position

Actual position of the motor for the A waveplate.

Not the same as "A Position" because of the 0 position correction specified in "A zero".



B Motor Position

Actual position of the motor for the B waveplate.

Not the same as "B Position" because of the 0 position correction specified in "B zero".



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc. Note that you might need to scroll down to see this control.



H HWP Measurement Angles (Hardy measurements only)

HWP angles at which probabilities that determine H will be measured. Determined from Alpha and Beta settings.

Useful so that you know which angles to set waveplates to when tweaking. Of course, for 2 detector measurements you need perpendicular combinations as well.

**H Pol Measurement Angles** (Hardy measurements with polarizers only)

Polarizer angles at which probabilities that determine H will be measured. Determined from Alpha and Beta settings.

Useful so that you know which angles to set waveplate to when tweaking. Of course, you need perpendicular combinations as well.

**Counts A, A', B, B'**

Singles counts in the time window specified by "Update Period" (upper left)

**Counts AB, A'B, AB', A'B'**

Coincidence counts in the time window specified by "Update Period" (upper left)

**P** (4-detector Hardy measurements only)

Probability of AB.

**P Meter** (4-detector Hardy measurements only)

Probability of AB

Data Taking Parameters**Update Period (Data Run)**

[Must be a multiple of 0.1s]

Time window (in s) for counters during data acquisition.

This applies after the "Take Data" button has been pressed.

**No. of Samples**

Number of independent measurements (of H for Hardy measurements, or S for Bell Measurements) that are made during data acquisition. These are averaged to get the mean and error of the measurement.

Error measurements are essentially useless if this is less than 5. 10 is a good number for reasonable statistics.



Take Data

Leave the setup "tweaking" mode and switch to data acquisition mode.

Bell Measurements

**E Meter** (4-detector Bell measurement only)

Expectation Value

**E** (4-detector Bell measurement only)

Expectation Value

**S HWP Measurement Angles**

HWP angles at which probabilities that determine S will be measured.

Useful for 4 detector measurements so that you know which angles to set waveplates to when tweaking. Angles labeled + correspond to expectations you want to be as positive as possible, while those labeled - should be as negative as possible.

Not particularly useful for 2 detector measurements.

**S Pol Measurement Angles**

Polarizer angles at which probabilities that determine S will be measured.

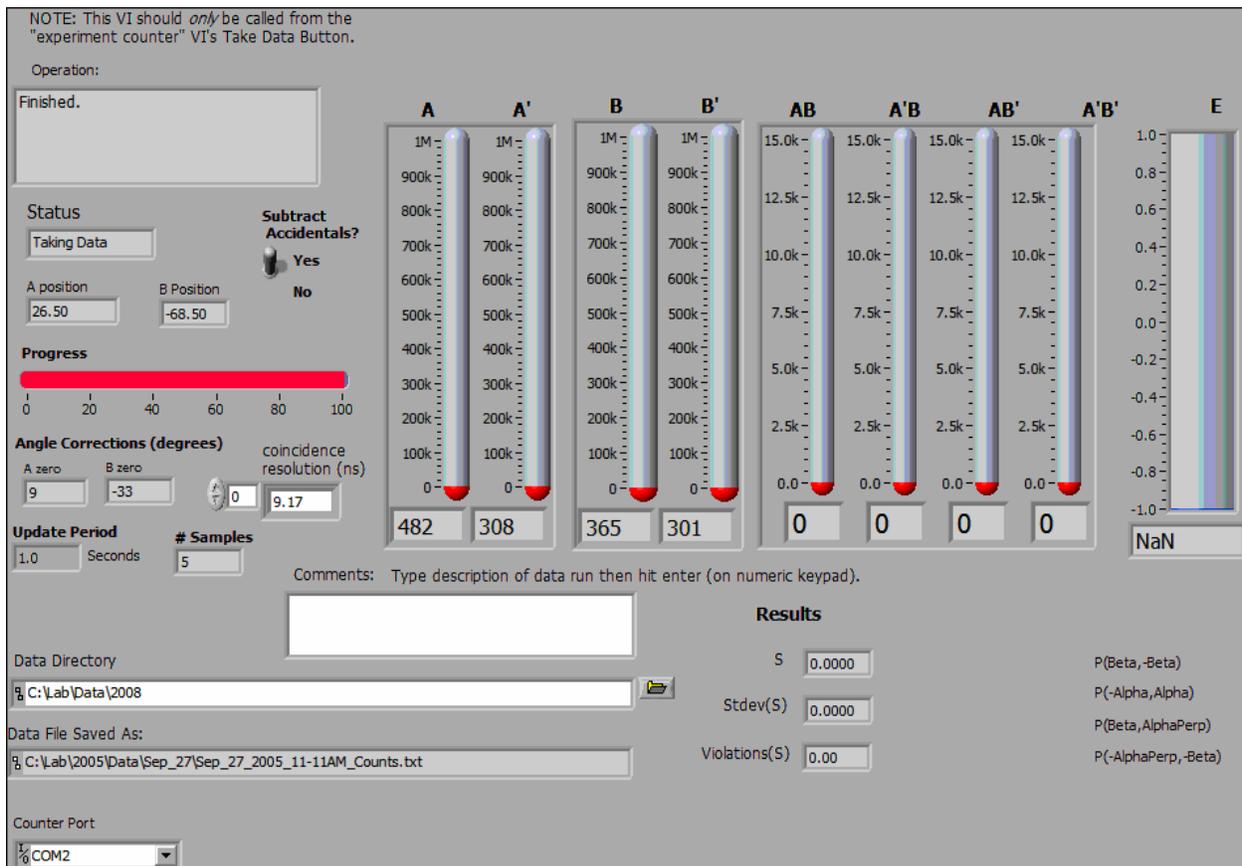
Not a particularly useful parameter for 2 detector measurements.

II. Taking Data

When you move to data taking mode, the program you see is:

Hardy-Bell-Recorder_rs232.vi

Front Panel



Description

This VI should ONLY be called from a "Hardy_Bell_rs232" VI--necessary parameters are set there.

This program records data (using parameters set in the "Hardy_Bell_rs232" VI) and saves the data to a file.

Controls and Indicators



Operation

Displays what the program is trying to do. Normally this shows what the angles of the motors are.

There are 2 angles shown -- the waveplate angles are given first and the actual motor angles are in parentheses (they are different by the 0 offset displayed in "A zero" and "B zero".)

When the program is done this reads "Finished." Values for probabilities (expectations for Bell) and H (S for Bell) are not updated until this happens.



Status

Program Status:

Moving Motors: waveplate (polarizer) motors are in motion.

Waiting: Clearing out the counter buffers after motors move.

Taking Data: Data is being collected.



A position

Current position of A motor.



B Position

Current position of B motor.



Subtract Accidentals?

Determines whether or not accidental coincidences are subtracted.



coincidence resolution (ns)

Array of the coincidence time resolutions (used in subtraction of accidentals).



Progress

Rough indication of what percentage of the data run is complete.



A zero Motor angle at which A waveplate axis is 0.



B zero Motor angle at which B waveplate axis is 0.

**Update Period**

Time window (in s) for counters.

**# Samples**

Number of independent measurements (of H for Hardy measurements, or S for Bell Measurements) that are made during data acquisition. These are averaged to get the mean and error of the measurement.

Error measurements are essentially useless if this is less than 5. 10 is a good number for reasonable statistics.

**Comments**

A space where you can enter comments about the data run. These get saved in the header of the data file.

Note that you must hit "Enter" on the NUMERIC KEYPAD, not the "Enter" (or "Return") on the regular keyboard for this text to be saved.

**Data Directory**

Path to directory where the data will be saved.

**Data File Saved As:**

Path to the data file. The data file is automatically named using the date and time.

**Alpha**

Angle Alpha used in the Hardy measurement.

**Beta**

Angle Beta used in the Hardy measurement.

**H (Hardy measurement only)**

Mean value of H. Updated when "operation" reads "Finished".

**Stdev(H) (Hardy measurement only)**

Standard Deviation of H. Updated when "operation" reads "Finished".

DBL **Violations(H)** (Hardy measurement only)

Number of standard deviations that H is above 1. Updated when "operation" reads "Finished".

DBL **P Stdev(P)**

Probabilities and standard deviations of the probabilities for the indicated angles. Updated when "Operation" reads "Finished".

DBL **P** (4 detector Hardy only)

Probability of AB

I/O **Counter Port**

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.

Bell Measurements

DBL **S** (Bell measurement only)

Mean Value of S. Updated when "Operation" reads "Finished".

DBL **Stdev(S)** (Bell measurement only)

Standard deviation of S. Updated when "Operation" reads "Finished".

DBL **Violations(S)** (Bell measurement only)

Number of standard deviations that S is above 2. Updated when "Operation" reads "Finished".

DBL **E** (4 detector Bell only)

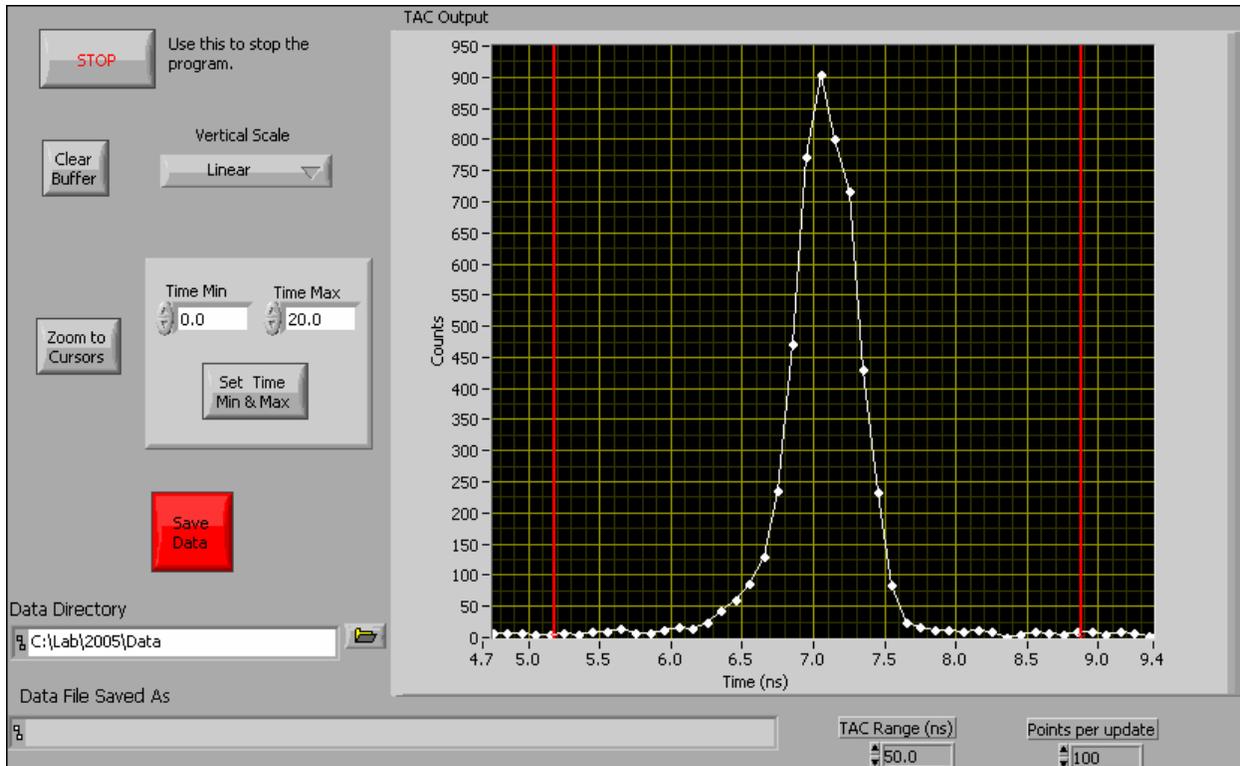
Expectation value.

Appendix C - MCA.vi

This appendix describes the LabView vi used to mimic the behavior of a multichannel analyzer (MCA). This is useful for measuring the arrival time of photons.

MCA.vi

Front Panel



Description

This VI emulates a multi-channel-analyzer (MCA). An MCA essentially digitizes a series of voltage pulses, and creates a histogram of the pulse heights. The purpose of this VI is to analyze the voltage pulses from a Time-to-Amplitude Converter (TAC) [This VI was tested using the TAC in an ORTEC 567 TAC/SCA module].

The start and stop pulses going into the TAC come from photon counters, and the TAC output voltage is proportional to the time between the start and stop. Thus, the MCA is creating a histogram of the time interval between the arrivals of the two photons.

The main difference between this VI and a real MCA is that an MCA takes only one input—the voltage pulses. This VI also needs timing information about when the pulses are arriving. Fortunately, this can be obtained from the Valid Conversion output of the TAC. The Valid Conversion output is an approximately 3 microsecond long TTL pulse coincident with the TAC output pulse.

We have tested this VI with 2 different National Instruments multifunction cards: 6036E and 6052E. With these cards there are two clock signals that are needed to perform an A/D conversion: the trigger and the sample clock.

The trigger (input through PFI0) comes directly from the Valid Conversion output of the TAC. The program is configured to trigger on a low-to-high transition of the trigger -triggering arms the A/D, but does not actually cause an A/D conversion.

The program is configured to perform an A/D conversion on a high-to-low transition of the Sample Clock. The Sample Clock is obtained by generating a delayed pulse from the trigger. The delayed pulse is generated by one of the counter/timers on the multifunction board: counter 0. The output of counter 0 is sent directly to the sample clock, so the user need only input the trigger pulse to PFI0, and the sample clock will take care of itself (the user can monitor the counter 0 output to observe the timing of the sample clock). The timing can be changed by adjusting the duration of the pulse (using the "High Time") parameter in the block diagram).

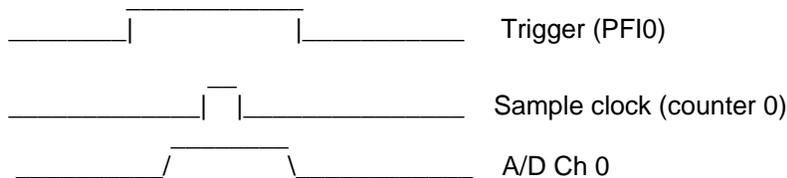
The TAC output to be digitized is input through Analog Input Channel 0.

Unlike many VI's you'll encounter, the screen updates after a specified number of data points are acquired (determined by the parameter "Points per update"), not after a specific time interval. Because of this, if the detectors are off, nothing will happen.

NOTE: The A/D boards we use are just barely fast enough to catch the 3 microsecond long TAC output (the width of the TAC output could also be increased for better results)--indeed, they're probably technically too slow. Because of this, the accuracy of the measurement of the TAC output is not very good (can be off by as much as 10 or 20%), which means that the time scale is poorly calibrated. However, the measurement is repeatable, so the time scale could be calibrated much more accurately. Despite this problem, the VI works quite well enough to accomplish its main goals-to display a bump in the histogram of arrival times between the photons from two detectors, and to allow one to set the SCA window to select coincidences (only needed if you're using the TAC/SCA for coincidence counting).

ALSO NOTE: This vi has only been seriously tested for START-STOP times ranging from a few up to about 30 ns. With much longer intervals than this the output pulses may be delayed, and the timing may change.

Rough Timing diagram:



Help for each of the controls and indicators can be obtained from the Contextual Help window <ctrl - H> by mousing over each control or indicator. Full documentation for each control and indicator can be obtained by printing using: File>Print>Custom, and then checking "All controls" and "Descriptions"

FINAL NOTE: For whatever reason, the vi "aquire_daqm_x_subvi.vi" does NOT get saved if you save the entire vi hierarchy. So, you explicitly need to copy this vi to the new library from the old one. After you copy it, LabView will STILL look for it in the old location, so you again need to explicitly find this vi for LabView.

Controls and Indicators

 **Stop**

Use this to stop.

**Clear Buffer**

Clears the histogram memory, and the accumulation starts over again.

**Vertical Scale**

Change the scaling of the vertical scale. Options are Linear and Logarithmic.

**Zoom to cursors**

Horizontal scale will zoom in to the region specified by the cursor positions.

**Time Min**

Set minimum of horizontal axis to this value after pressing "Set Time Min & Max".

**Time Max**

Set maximum of horizontal axis to this value after pressing "Set Time Min & Max".

**Set min & max**

Set the minimum and maximum values of the horizontal axis to those specified.

**Save Data**

Save the current data to a file. Program exits after this is done.

**Data Directory**

Path to directory where the data will be saved.

**Data File Saved As**

Path to the data file. The data file is automatically named using the date and time.

**TAC Range (ns)**

The full scale range of the TAC output. Used to scale the horizontal axis.

**Points per update**

Number of data points acquired before updating the screen. Remember, the screen updates after a specified number of data points are acquired, not after a specific time interval.

If you have very low count rates, you might want to decrease this from its default value of 100.



TAC Output

Histogram of the time interval distribution.

Appendix D – Coincidence_time_res_rs232.vi

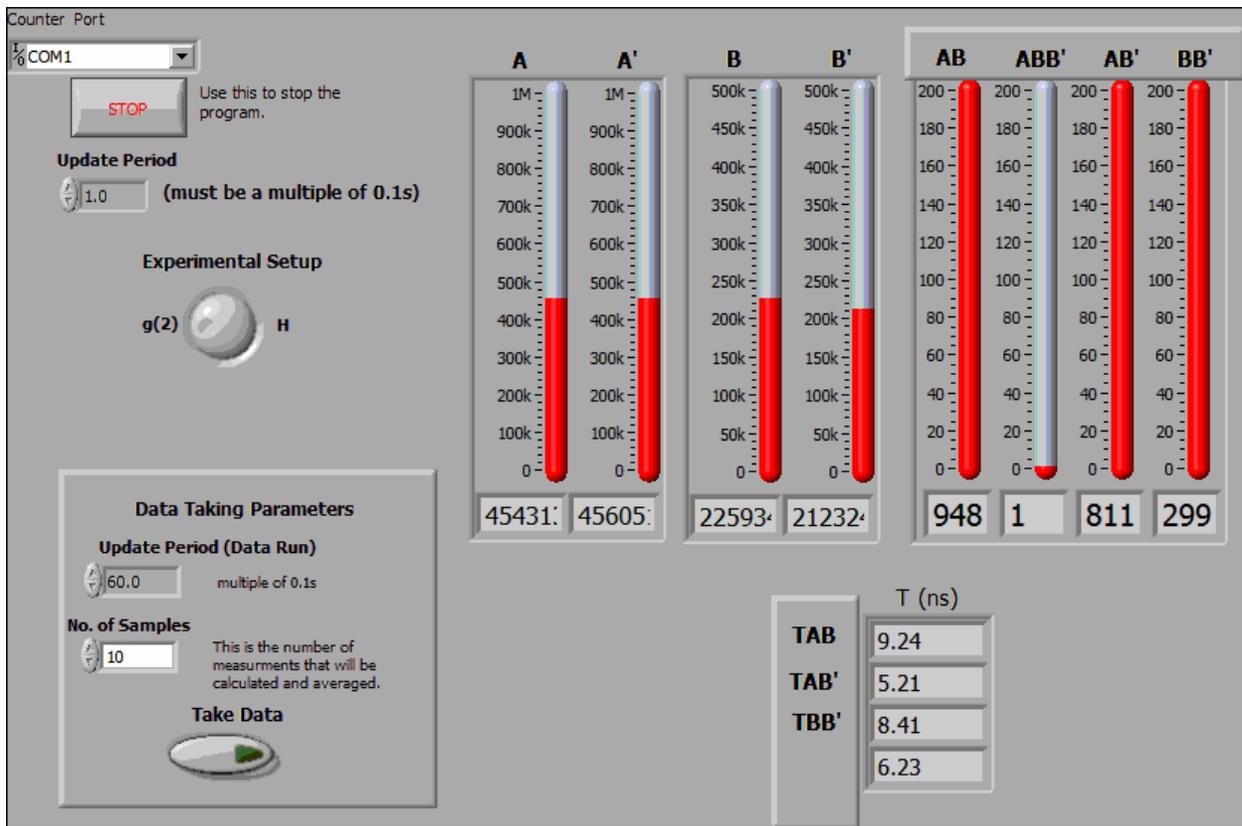
This appendix describes the LabView vi used to calibrate the coincidence time resolution.

I. Starting Out

The appearance of this vi will change slightly depending on the experiment you are doing (as determined by the **Experimental Setup** knob on the vi.)

Coincidence_time_res_rs232.vi

Front Panel



Description

This is the program you use to calibrate the coincidence time resolution of your coincidence circuit. It was specifically written for the Altera DE2 counter. Data streams to the computer from the DE2 over the RS232 serial port.

In order to get accurate readings, the SPCMs must be illuminated by uncorrelated random streams of photons. One way to do this is to simply place a white card after the downconversion crystal to scatter blue pump light. There are plenty of scattered photons to get through the RG780 blocking filters. The intensity level can be adjusted somewhat by moving the card closer or further away from the exit face of the crystal. Adjusting iris diameters can help as well. 500k to 1M singles cps on each detector works

well.

For example, with random photons the coincidence time resolution T_{AB} for AB coincidences is $T_{AB} = (AB \cdot T) / (A \cdot B)$, where T is the counting time, AB the number of coincidences, and A and B the number of singles.

There are 2 modes:

1) g(2) measures the resolution for AB, AB' and BB' coincidences. (random photons do not give an accurate measurement of the ABB' triple time because for those measurements you WANT at least one valid coincidence).

2) H measures the time resolution for AB, A'B, AB' and A'B' coincidences.

NOTE: The coincidence determination switches on the DE2 must be matched to the "Experimental Setup" switch here on the vi—appropriate switch settings are given below.

The program does not record data to a file right away, but displays the counters in real time so that you can align things.

Once everything is aligned and the parameters are set, you press the "Take Data" button. This transfers control to another program which records a data set and saves it to a file.

The DE2 board must be properly set to record the proper coincidences. The coincidences that should be mapped to a given counter are:

When set to g(2):

A (Counter 0)

B (Counter 1)

A' (Counter 2) – unused for g(2) measurements

B' (Counter 3)

AB (Counter 4)

ABB' (Counter 5) – used for g2 measurements, but not by this program

AB' (Counter 6)

BB' (Counter 7)

When set to H:

A (Counter 0)

B (Counter 1)

A' (Counter 2)

B' (Counter 3)

AB (Counter 4)

A'B (Counter 5)

AB' (Counter 6)

A'B' (Counter 7)

On startup, the program initializes the com port.

After initialization the program simply loops and displays the counts in a given time window (determined

by the "Update Period" control in the upper left.) This is useful for tweaking the alignment and adjusting parameters.

Nothing is written to disk until the parameters are chosen and the "Take Data" button is pressed. This loads a second VI that records and saves data to disk. Parameters for this data acquisition phase are set in the "Data Taking Parameters" box.

Help for each of the controls and indicators can be obtained from the Contextual Help window <ctrl - H> by mousing over each control or indicator. Full documentation for each control and indicator can be obtained by printing using: File>Print>Custom, and then checking "All controls" and "Descriptions".

Controls and Indicators



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.



Experimental Setup

Which calibration to perform.

- 1) g(2) measures the resolution for AB, AB' and BB' coincidences.
- 2) H measures the time resolution for AB, A'B, AB' and A'B' coincidences.



Update Period

[Must be a multiple of 0.1s]

Time window (in s) for the counters during setup phase (i.e., before the "Take Data" button is pressed.)



Stop

Use this to stop. It takes a little longer, but this way, the board gets reset. If you stop some other way you'll probably need to quit Labview and restart; you may even need to reboot the computer.



Counts A, A', B & B'

Singles counts in the time window specified by "Update Period" (upper left)



Coincidences

AB, A'B, AB', A'B' for H measurements

AB, ABB', AB', BB' for g2 measurements.

Coincidence counts (doubles or triples as indicated) in the time window specified by "Update Period" (upper left)



T (ns)

Values of coincidence time resolution (in ns) for the current iteration.



No. of Samples

Number of independent measurements that are made during data acquisition. These are averaged to get the mean and error of the measurement.

Error measurements are essentially useless if this is less than 5. 10 is a good number for reasonable statistics.



Update Period (Data Run)

Time window (in S) for counters during data acquisition.

This applies after the "Take Data" button has been pressed.



Take Data

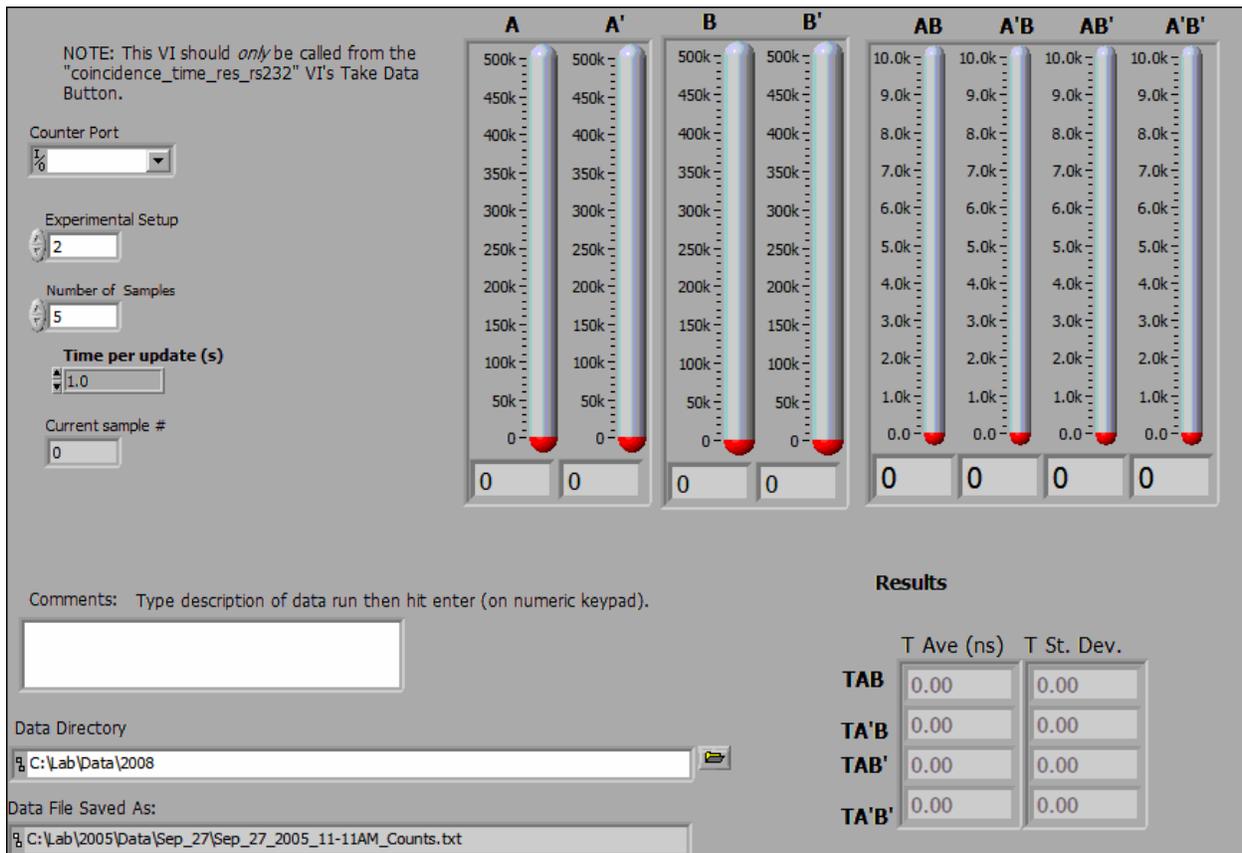
Leave the setup "tweaking" mode and switch to data acquisition mode.

II. Taking Data

When you move to data taking mode, the program you see will look something like that shown below. Again, the appearance of this vi will change slightly depending on the calibration you are doing.

coincidence_time_res_recorder.vi

Front Panel



Description

This VI should ONLY be called from an "coincidence_time_res_rs232" VI--necessary parameters are set there.

This program records data (using parameters set in the "coincidence_time_res_rs232" VI) and saves the data to a file.

Controls and Indicators



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.



Experimental Setup

Which calibration is being performed.

1: g2 calibration

2: H calibration



Number of Samples

Number of independent measurements that are made during data acquisition. These are averaged to get the mean and error of the measurement.



Time per update (s)

Time window (in s) of counters during data acquisition.



Current sample #

Which sample number is presently being measured.



Counts A, A', B & B'

Singles counts in the time window specified by "Time per update"



Coincidences

AB, A'B, AB', A'B' for H measurements

AB, ABB', AB', BB' for g2 measurements.

Coincidence counts (doubles or triples as indicated) in the time window specified by "Time per update"



Comments

A space where you can enter comments about the data run. These get saved in the header of the data file.

Note that you must hit "Enter" on the NUMERIC KEYPAD, not the "Enter" (or "Return") on the regular keyboard for this text to be saved.



Data Directory

Path to directory where the data will be saved.

**Data File Saved As:**

Path to the data file. The data file is automatically named using the date and time.

**T Ave (ns)**

Measured average time resolution in ns.

**T St. Dev.**

Standard deviation of the measured time resolutions in ns.

Appendix E – Angle_scan_rs232.vi

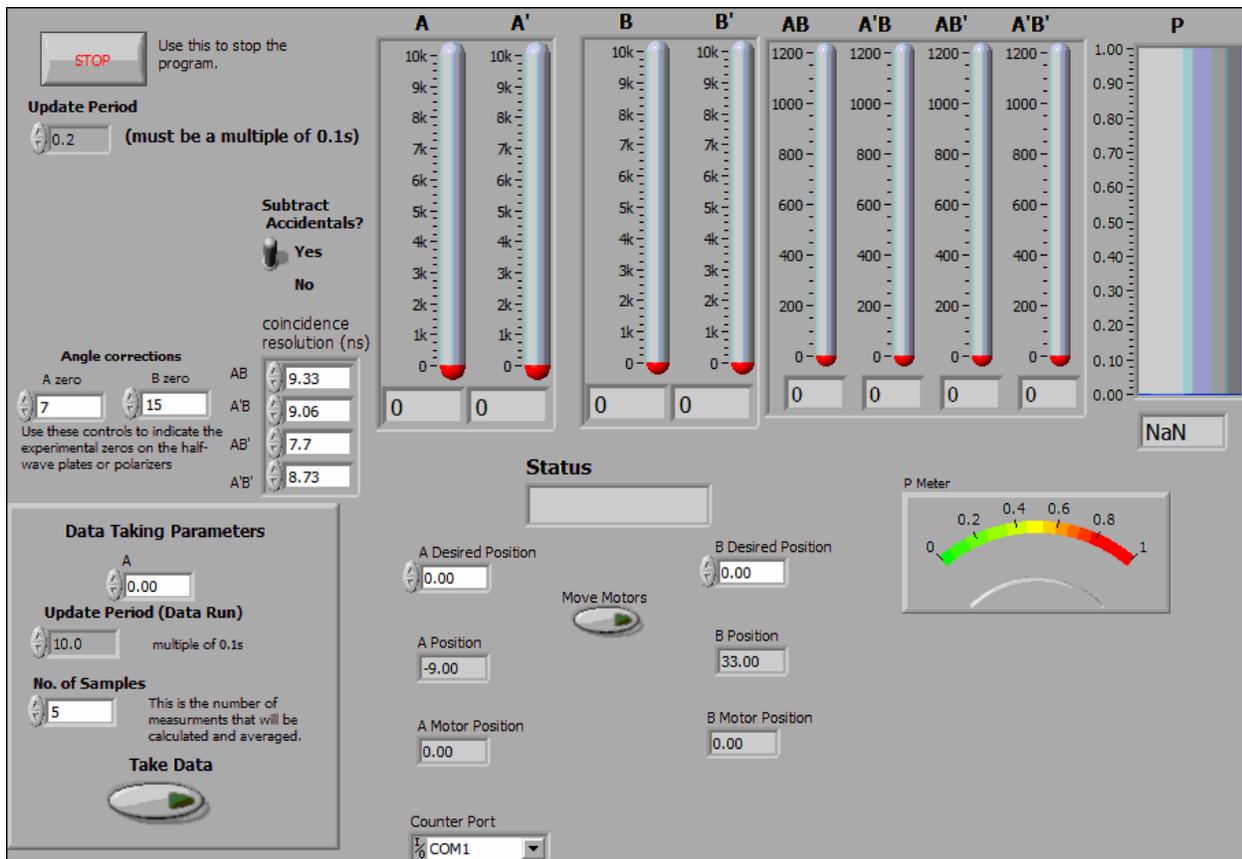
This appendix describes the LabView vi used to examine two photon polarization correlations (joint probabilities) as a function of angle.

I. Starting Out

When you first run the vi, the program that you see is:

Angle_scan_rs232.vi

Front Panel



Description

This is the program you see first when you start to run the experiment. It requires a 4-detector setup. It does not record data to a file right away, but displays the counters in real time so that you can align things. It also gives you interactive control over such things as the waveplate angles.

Once everything is aligned and the parameters are set, you press the "Take Data" button. This transfers control to another program which records a data set and saves it to a file.

This vi was specifically written for the Altera DE2 counter. Data streams to the computer from the DE2 over the RS232 serial port.

Waveplates (or polarizers) are controlled by a Newport ESP300 controller at GPIB address 1. On program start, during initialization, the motors home themselves. The motors then set the waveplates to 0 (using the corrections in "A zero" and "B zero").

The DE2 board must be properly set to record the proper coincidences. The coincidences that should be mapped to a given counter are:

A (Counter 0)

B (Counter 1)

A' (Counter 2)

B' (Counter 3)

AB (Counter 4)

A'B (Counter 5)

AB' (Counter 6)

A'B' (Counter 7)

On startup, the program initializes the motors and the counters. During this time the "Status" indicator reads "Initializing".

After initialization the program simply loops and displays the counts in a given time window (determined by the "update Period" control in the upper left.) Status reads "Reading Counters". This is useful for tweaking the alignment and adjusting parameters. Waveplates (or polarizers) are moved by first setting the desired waveplate angles in the " A(B) Desired Position" controls, and then pressing the "Move Motors" button. Status changes to "Moving Motors" while the motors are in motion.

Nothing is written to disk until the parameters are chosen and the "Take Data" button is pressed. This loads a second VI that records and saves data to disk. Parameters for this data acquisition phase are set in the "Data Taking Parameters" box.

During data acquisition the motors will automatically set the waveplates to the correct angles. The waveplate for the A beam is fixed by the Data Taking Parameter "A". The angle of waveplate B is scanned over 17 equally spaced values: 0, 5.625, 11.25, ... Remember that these are WAVEPLATE angles; since polarization rotates twice as fast as the waveplate, the corresponding polarization angles are twice as large. So, the A polarization angle is twice what is set by the A control, while the B polarization angles are 0, 11.25, 22.5, ... What gets recorded in the data file are waveplate angles, not polarization angles.

Help for each of the controls and indicators can be obtained from the Contextual Help window <ctrl - H> by mousing over each control or indicator. Full documentation for each control and indicator can be obtained by printing using: File>Print>Custom, and then checking "All controls" and "Descriptions".

Controls and Indicators



Stop

Use this to stop. If you stop some other way you'll probably need to quit Labview and restart; you may even need to reboot the computer.



Update Period

[Must be a multiple of 0.1s]

Time window (in s) for the counters during setup phase (i.e., before the "Take Data" button is pressed.) Readings update once each time window if "Status" reads "Reading Counters".



A zero

Motor angle at which A waveplate axis is 0.

**B zero**

Motor angle at which B waveplate axis is 0.

**Subtract Accidentals?**

Determines whether or not accidental coincidences are subtracted. Controls data taking mode as well as tweaking mode.

**coincidence resolution (ns)**

The coincidence time resolutions (used in subtraction of accidentals).

**Status**

Program Status:

Initializing: initializing the counters and motors.

Reading Counters: Program is looping, reading the counters and updating the screen.

Moving Motors: Waveplates (polarizers) are rotating.

**A Desired Position**

Angle to set A waveplate to.

Movement occurs after "Move Motors" button is pressed.

**B Desired Position**

Angle to set B waveplate to.

Movement occurs after "Move Motors" button is pressed.

**Move Motors**

Set the motors to the "Desired Positions"

**A Position**

Current angle of the A waveplate.

**B Position**

Current angle of the B waveplate.



A Motor Position

Actual position of the motor for the A waveplate.

Not the same as "A Position" because of the 0 position correction specified in "A zero".

**B Motor Position**

Actual position of the motor for the B waveplate.

Not the same as "B Position" because of the 0 position correction specified in "B zero".

**Counter Port**

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc. Note that you might need to scroll down to see this control.

**Counts A, A', B, B'**

Singles counts in the time window specified by "Update Period" (upper left)

**Counts AB, A'B, AB', A'B'**

Coincidence counts in the time window specified by "Update Period" (upper left)

**P**

Probability of AB.

**P Meter**

Probability of AB

Data Taking Parameters**A**

Angle of A waveplate--fixed for duration of the data taking.

**Update Period (Data Run)**

[Must be a multiple of 0.1s]

Time window (in s) for counters during data acquisition.

This applies after the "Take Data" button has been pressed.



No. of Samples

Number of independent measurements that are made during data acquisition. These are averaged to get the mean and error of the measurement.

Error measurements are essentially useless if this is less than 5. 10 is a good number for reasonable statistics.



Take Data

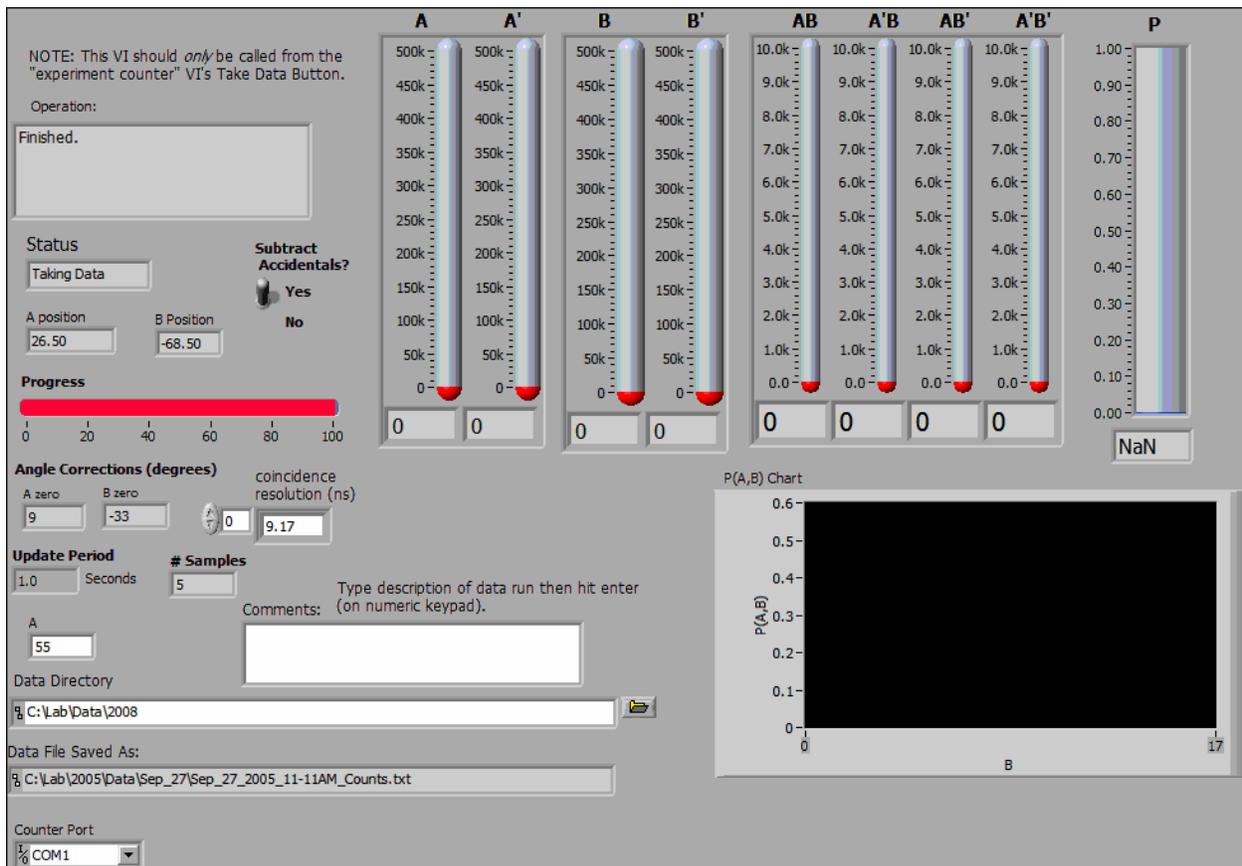
Leave the setup "tweaking" mode and switch to data acquisition mode.

II. Taking Data

When you move to data taking mode, the program you see is:

angle_scan_Recorder_rs232.vi

Front Panel



Description

This VI should ONLY be called from an "angle_scan_rs232" VI--necessary parameters are set there.

This program records data (using parameters set in the "angle_scan_rs232" VI) and saves the data to a file.

Controls and Indicators



Operation

Displays what the program is trying to do. Normally this shows what the angles of the motors are.

There are 2 angles shown -- the waveplate angles are given first and the actual motor angles are in parentheses (they are different by the 0 offset displayed in "A zero" and "B zero".)

When the program is done this reads "Finished." Values for probabilities (expectations for Bell) and H (S for Bell) are not updated until this happens.



Status

Program Status:

Moving Motors: waveplate (polarizer) motors are in motion.

Waiting: Clearing out the counter buffers after motors move.

Taking Data: Data is being collected.



A position

Current position of A motor.



B Position

Current position of B motor.



Subtract Accidentals?

Determines whether or not accidental coincidences are subtracted.



coincidence resolution (ns)

Array of the coincidence time resolutions (used in subtraction of accidentals).



Progress

Rough indication of what percentage of the data run is complete.



A zero Motor angle at which A waveplate axis is 0.



B zero Motor angle at which B waveplate axis is 0.



Update Period

Time window (in s) for counters.



Samples

Number of independent measurements (of H for Hardy measurements, or S for Bell Measurements) that are made during data acquisition. These are averaged to get the mean and error of the measurement.

Error measurements are essentially useless if this is less than 5. 10 is a good number for reasonable statistics.



A

Angle of A waveplate--fixed for duration of the data taking.



Comments

A space where you can enter comments about the data run. These get saved in the header of the data file.

Note that you must hit "Enter" on the NUMERIC KEYPAD, not the "Enter" (or "Return") on the regular keyboard for this text to be saved.



Data Directory

Path to directory where the data will be saved.



Data File Saved As:

Path to the data file. The data file is automatically named using the date and time.



P

Probability of AB



P(A,B) Chart

Plot of the joint probability $P(A,B)$ as the B waveplate is scanned.



Counter Port

A string that identifies the serial communication port that the DE2 board is attached to: "COM1", "COM2", etc.