LAB 5

Testing Local Realism

LAB TICKET

Create a spreadsheet that calculates $P(-\alpha,\alpha)$, $P(\beta,-\beta)$, $P\left(\beta,\alpha^{\perp}\right)$, $P\left(-\alpha^{\perp},-\beta\right)$, and H, given the state $\left|\psi_1\right\rangle$ in eq. (L5.13) below. For the fixed value $\alpha=35^{\mathrm{o}}$, make plots of $P\left(\beta,\alpha^{\perp}\right)$, $P\left(-\alpha^{\perp},-\beta\right)$, and H as functions of β (use values of β between 0^{o} and 90^{o}). How can you maximize H, while still keeping $P\left(\beta,\alpha^{\perp}\right)$, $P\left(-\alpha^{\perp},-\beta\right)$ less than 0.01?

L5.1 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 preformed somewhere else. By realism we mean that objects have values for measurable quantities, regardless of whether or not we measure them. According to local realism, if two photons are produced by a source, their polarizations are completely defined once they leave the source. Thus, polarization measurements performed on one photon should not 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 sec. 8.4 and complement 8.B.[1] You will also perform another test, one that uses a "Bell inequality" that was originally derived by Clauser, Horne, Shimony and Holt (CHSH). This is a historically important test of local realism, which has been

1. See also refs. [L5.1]–[L5.5].

around longer than Hardy's test. We'll describe the basics of this test below, but for more details see ref. [L5.6], and the references therein.

The experimental apparatus is shown in fig. L5.1 (see also fig. 8.3). The downconversion source is similar to the one we've used in previous labs, 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. As described in sec. 8.4, this source produces photons in the state

$$\left|\psi\right\rangle = \sqrt{a}\left|H\right\rangle_A \left|H\right\rangle_B + \sqrt{1-a}\; e^{i\varphi}\left|V\right\rangle_A \left|V\right\rangle_B . \tag{L5.1}$$

Experimentally, to change the ratio of the probability of the production of horizontally or vertically polarized pairs (the parameter a), you rotate the half-wave plate in the pump beam, which changes the pump polarization (e.g., if the pump has a larger horizontal component, then vertically polarized output photons are more likely). The birefringent plate in the pump beam is used to adjust the relative phase φ. With this experimental arrangement, we can create polarization states with any arbitrary linear combinations of the states $\left|H\right\rangle_A \left|H\right\rangle_B$ and $\left|V\right\rangle_A \left|V\right\rangle_B$.

The idler photon travels to Alice and her two detectors (**A** and **A′**), while the signal photon travels to Bob and his two detectors (**B** and **B′**). We are interested in signal-idler pairs where Alice and Bob detect photons at the same time, and the raw data collected in the experiment consists of measuring numbers of coincidence counts in a given time window ($N_{AB'}$ is the number of coincidences between detectors **A** and **B′** in a given counting interval, for example.)

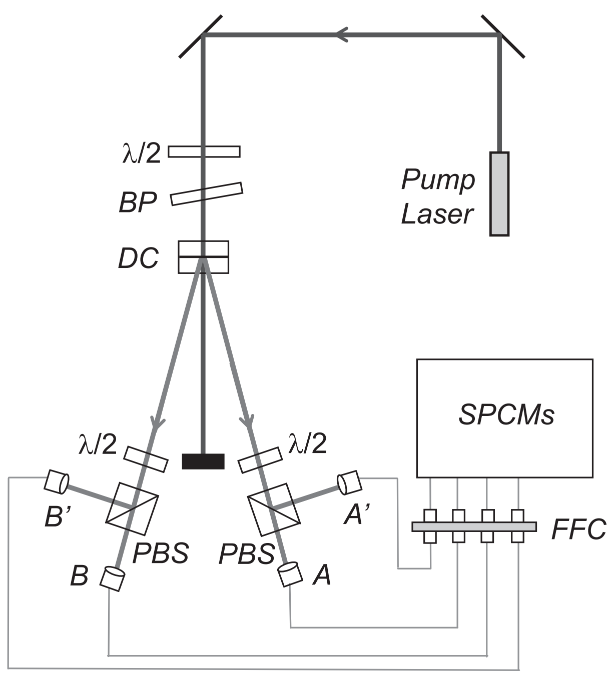

Fig L5.1 The experimental apparatus. Here λ/2 denotes a half-wave plate, BP denotes a birefringent plate, DC denotes the downconversion crystals, PBS denotes a polarizing beam splitter, FFC denotes fiber-to-fiber coupler, and SPCMs denotes the single-photon-counting modules.

Given the four measurements of coincidence counts (N_{AB}, $N_{AB'}$, $N_{A'B}$, and $N_{A'B'}$) we can determine the probability that Alice's and Bob's photons had a particular set of polarizations. For example, assume that Alice's half-wave plate is set to transmit photons polarized along the angle θ_A to detector **A**, and Bob's half-wave plate is set to transmit photons polarized along the angle θ_B to detector **B**. The joint probability that they will measure photons polarized along these directions, $P\left(\theta_A, \theta_B\right)$ is given by

$$P\left(\theta_A, \theta_B\right) = \frac{N_{AB}}{N_{AB} + N_{AB'} + N_{A'B} + N_{A'B'}}. \tag{L5.2 }$$

We will assume that in joint probabilities of the form $P\left(\theta_A, \theta_B\right)$, the first variable always refers to Alice's polarization.

L5.2 THEORY

L5.2.1 Hardy Test

Hardy's test of local realism is described in detail in sec. 8.4 and complement 8.B. In the idealized situation presented in sec. 8.4, this test involves testing the classical inequality

$$P\left(\theta_{A1}, \theta_{B1}\right) \le P\left(\theta_{A2}, \theta_{B2}\right). \tag{L5.3}$$

However, in complement 8.B we show that this inequality is simply a special case of the more general, experimentally testable, Bell-Clauser-Horne inequality [eq. (8.B.10)]:

$$P\left(\theta_{A1}, \theta_{B1}\right) \le P\left(\theta_{A2}, \theta_{B2}\right) + P\left(\theta_{A1}, \theta_{B2}^{\perp}\right) + P\left(\theta_{A2}^{\perp}, \theta_{B1}\right), \tag{L5.4}$$

where $\theta^{\perp} = \theta \pm 90^{\text{o}}$. In our experiment the angles of interest are two angles, α and β, and their negatives. By assigning $\theta_{A1} = \beta$, $\theta_{B1} = -\beta$, $\theta_{A2} = -\alpha$ and $\theta_{B2} = \alpha$, eq. (L5.4) becomes

$$P(\beta, -\beta) \le P(-\alpha, \alpha) + P\left(\beta, \alpha^{\perp}\right) + P\left(-\alpha^{\perp}, -\beta\right). \tag{L5.5}$$

It is convenient to define the quantity H, where

$$H \equiv P(\beta, -\beta) - P(-\alpha, \alpha) - P\left(\beta, \alpha^{\perp}\right) - P\left(-\alpha^{\perp}, -\beta\right). \tag{L5.6}$$

In terms of H, the Bell-Clauser-Horne inequality is $H \le 0$.

As described in complement 8.B, if we measure $H \le 0$, then the data are consistent with local realism. If we measure $H > 0$, then local realism is violated, and we are forced to abandon some of our classical ideas.

L5.2.2 CHSH Test

Here we describe the CHSH inequality, but we will not prove it. For a proof of this inequality, see ref. [L5.6].

The CHSH inequality involves a particular combination of expectation values. Consider the polarization operator defined in chap. 5. The eigenstates and eigenvalues of the polarization operator for linear polarization along the angle θ are

$$\hat{\wp}_\theta \left|\theta\right\rangle = (+1)\left|\theta\right\rangle,\ \hat{\wp}_\theta \left|\theta^\perp\right\rangle = (-1)\left|\theta^\perp\right\rangle. \tag{L5.7}$$

The joint polarization operator for Alice and Bob is defined as

$$\hat{\wp}^{AB}_{\theta_A\theta_B} = \hat{\wp}^{A}_{\theta_A}\hat{\wp}^{B}_{\theta_B}. \tag{L5.8}$$

It is traditional to represent the expectation value of this joint polarization operator as

$$E(\theta_A,\theta_B) \equiv \left\langle \hat{\wp}^{AB}_{\theta_A\theta_B} \right\rangle = P(\theta_A,\theta_B) + P(\theta_A^\perp,\theta_B^\perp) - P(\theta_A^\perp,\theta_B) - P(\theta_A,\theta_B^\perp), \tag{L5.9}$$

and to define the quantity S as

$$S \equiv E(\theta_{A1},\theta_{B1}) + E(\theta_{A2},\theta_{B1}) - E(\theta_{A2},\theta_{B2}) + E(\theta_{A1},\theta_{B2}). \tag{L5.10}$$

In a universe that is consistent with local realism, S satisfies the inequality $|S| \leq 2$, for any choices of the angles.

However, assume that the photons are prepared in the Bell state:

$$\left|\phi^+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_A\left|H\right\rangle_B + \left|V\right\rangle_A\left|V\right\rangle_B\right). \tag{L5.11}$$

For this state, and for proper combinations of angles, quantum mechanics predicts $S = 2\sqrt{2}$, which yields a maximal violation of the CHSH inequality.

Q1: Prove that the expectation value $E(\theta_A,\theta_B)$ is given by the combination of probabilities in eq. (L5.9).

Q2: For the state $\left|\phi^+\right\rangle$, and the angles $\theta_{A1} = 0^{\circ}$, $\theta_{B1} = 22.5^{\circ}$, $\theta_{A2} = 45^{\circ}$, and $\theta_{B2} = -22.5^{\circ}$, show that the quantum mechanical prediction yields $S = 2\sqrt{2}$.

L5.3 ALIGNMENT

Note to instructors: To save time in the lab, the alignment described in this section could be done ahead of time. Students would then begin their lab work with sec. L5.4.

- Begin with the pump-beam half-wave plate set so that the pump is vertically polarized when it strikes the downconversion crystal pair. In this orientation, only one of the downconversion crystals is being pumped, and the polarization state of the downconverted photons is that of eq. (L5.1) with $a = 1$, i.e., $|\psi\rangle = |H\rangle_A |H\rangle_B$.
- Following the procedure in lab 1, align the crystal, and detectors **A** and **B**.
- Following the procedure in lab 2, align the polarizing beam splitters, wave plates, and detectors **A′** and **B′**.
- So far, we have been aligning the system by pumping only one of the downconversion crystals. This first crystal is sensitive to tilt in one direction, but not the other. For a vertically polarized pump, the crystal should be sensitive to tilt in the vertical direction, but not in the horizontal direction.
- In order to align the second crystal, rotate the pump-beam wave plate by 45°, which rotates the pump-beam polarization to horizontal. Now the second crystal is being pumped, but not the first. Adjust the horizontal tilt of the crystal pair to maximize the count rates. The second crystal should be sensitive to this tilt, but the alignment of the first crystal will not be affected because it is not sensitive to this tilt. This tilt is the only adjustment you should need to make in order to align the second crystal, and complete the alignment.

In the next section, you will adjust the pump-beam wave plate and the birefringent plate, in order to create the proper polarization-entangled state.

L5.4 CREATING THE BELL STATE

- Run the LabVIEW program “Angle_scan.vi”.

Documentation for this program comes with the software. It starts by initializing the counters and the motors which control the wave-plate 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 lab 1 (sec. L1.7), 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 may 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.

When the program is done initializing, the **A** and **B** wave plate angles are set to zero (double check that the **A Position** and **B Position** parameters read 0). With these wave plates settings the **A** and **B** detectors monitor horizontally polarized photons coming from the source, and the **A′** and **B′** detectors monitor vertically polarized photons. Recall that the state of the downconverted photons is given by eq. (L5.1), with the parameters a and φ determined by the settings of the half-wave plate and the birefringent plate in the pump beam.

- Adjust the pump-beam half-wave plate to roughly equalize the **AB** coincidences and **A′B′** coincidences. Given that the source produces photons in the state of eq. (L5.1), and the wave-plate axes are set to 0°, you should notice that there are **AB** and **A′B′** coincidences, but essentially no **A′B** or **AB′** coincidences (there are always a few due to experimental imperfections).

Q3: Why is this? Calculate the probability of an **A′B** or **AB′** coincidence given the state in Eq. (L5.1).

- If you do notice significant **A′B** or **AB′** coincidences, it probably means that the **A** and/or **B** wave plates are not properly zeroed. Enter 0 for the **A Desired Position** and the **B Desired Position** parameters, then push the **Move Motors** button. The wave plates should rotate to 0: **A Position** and **B Position** should read 0. Note, however, that the **A Motor Position** and **B Motor Position** displays will not necessarily read zero; they will read the values given in the **A zero** and **B zero** parameters. These parameters are needed because the 0 angles of the motors are not necessarily perfectly aligned with the 0 angles of the wave plates.

  Slightly adjust (in about 1° increments) the rotation angles of the wave plates by entering values into **A Desired Position** and the **B Desired Position** parameters, then push the **Move Motors** button. Once you've minimized the **A′B** and **AB′** coincidences, note the readings in the **A Motor Position** and **B Motor Position**—these are the correct 0 readings, and you should enter them as the **A zero** and **B zero** parameters.
- Once the correct **A zero** and **B zero** parameters have been entered, the program must be stopped and then restarted in order to recognize the new values. Write down these correct values, because any time you quit and restart LabVIEW you may need to reenter them.
- Rotate the wave plate 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** and **A′B′** coincidences, but you should never produce any significant **A′B** or **AB′** coincidences.

- Adjust the wave plate in the pump beam so that the **AB** and **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.

Q4: What happens to the coincidence rates? Explain this.

- 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.
- Set the **A** and **B** wave plates to 0°. Adjust the pump-beam half-wave plate so that the ratio of the **AB** and **A′B′** coincidences is roughly 1:1.
- Now use the motors to set the **A** and **B** wave plates to 22.5°. Adjust the tilt of the birefringent plate in the pump beam (NOT the pump-beam half-wave plate) to minimize the **A′B** and **AB′** coincidences. You won't be able to get these coincidences to be as low as with the wave plates 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** and **B** wave plates set to 0°, adjust the ratio of the **AB** and **A′B′** coincidences to be equal using the pump-beam half-wave plate; with the **A** and **B** wave plates set to 22.5°, minimize the **A′B** and **AB′** coincidences with the tilt of the birefringent plate. You should notice that even with the **A** and **B** wave plates set to 22.5°, the ratio of the **AB** and **A′B′** coincidences should still be roughly 1:1.

Now the state of your downconverted photons should be given approximately by the Bell state $\left|\phi^{+}\right\rangle$ of eq. (L5.11). Consider how we know this:

Q5: With the **A** and **B** wave plates set to 0°, detectors **A** and **B** are measuring horizontally polarized photons from the source, and detectors **A′** and **B′** are measuring vertically polarized photons from the source. If the **AB** and **A′B′** coincidences are equal, what do we know about the parameter a in eq. (L5.1)? 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 wave plates set to 0° determines the parameter a, but not φ. In order to determine φ, you need to use the results of your measurements with the wave plates set to 22.5°.

Q6: 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 **A** and **B** wave plates set to 22.5°? (Ignore your experimental inability to make this coincidence rate perfectly 0.) Write down the state produced by the source.

Q7: Given the state you just determined, calculate the joint probability $P(\theta_A, \theta_B)$ that Alice will measure her photon to be polarized along θ_A, and Bob will find his photon polarized along θ_B.

L5.5 EXPLORING QUANTUM CORRELATIONS—ENTANGLED 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.

Now you're ready to scan one of the wave-plate angles, and measure the joint probability $P(\theta_A, \theta_B)$. The program "Angle_scan.vi" is designed to fix θ_A, and scan θ_B over a preset range of angles. **NOTE: the computer scans (and records in a datafile) a *wave-plate* 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 wave plate angles, because the angle of the output polarization from a wave plate rotates twice as fast as the rotation angle of the wave plate.**

- In the **Data Taking Parameters** section, set **A** to 0 (this is the fixed wave-plate 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 the **B** wave-plate angle between 0° and 90°.
- Repeat this experiment with **Angle A** set to 22.5° (corresponding to a polarizer angle of 45°).

In your lab report you should create two graphs. The first is theory and experiment for $P(\theta_A = 0^\circ, \theta_B)$, 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 Q7.

In chapter 8, we talked about the difference between an entangled state and a mixed state. Equation (L5.11) assumes an entangled state—in other words, that at any given time the photons are in both the states $|H\rangle_A |H\rangle_B$ and $|V\rangle_A |V\rangle_B$. 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?

Q8: Calculate the probability $P(\theta_A, \theta_B | H_A, H_B)$—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 $|H\rangle_A |H\rangle_B$.

Q9: Calculate the probability $P(\theta_A, \theta_B | V_A, V_B)$.

Q10: If you refer back to sec. 8.3, you'll see that the probability of joint polarization measurements in a mixed state is

$$P_{mix}(\theta_A,\theta_B) = P(\theta_A,\theta_B|H_A,H_B)P(H_A,H_B) + P(\theta_A,\theta_B|V_A,V_B)P(V_A,V_B), \quad \text{(L5.12)}$$

where $P(H_A,H_B)$ is the probability that the photons are produced in the state $|H\rangle_A|H\rangle_B$, and similarly for $P(V_A,V_B)$. 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.

Q11: 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 $P(H_A,H_B)$ and $P(V_A,V_B)$ that will allow $P_{mix}(\theta_A,\theta_B)$ to agree with both data sets?

Remember, if the data are consistent with an entangled state, we must conclude that although the polarizations of the two photons are perfectly correlated with each other, neither photon is in a well-defined state before a measurement.

L5.6 TESTING THE CHSH INEQUALITY

The Bell state $|\phi^+\rangle$ you've created is the ideal state to test the CHSH inequality, so let's perform this test.

- Close "Angle_scan.vi," as it cannot be in memory while running "Hardy-Bell.vi."
- Open the LabVIEW program "Hardy-Bell.vi", set the **A zero** and **B zero** parameters to the values you previously determined, then run the program.
- 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 you're in the Bell state $|\phi^+\rangle$. The **AB** and **A′B′** coincidences should be roughly equal, and these coincidences should be maximized while the **A′B** and **AB′** coincidences are minimized. This should be true with the **A** and **B** wave plates at both 0° and 22.5°. A good figure of merit for this is the "E-meter"—the big blue bar on the right. The E-meter reads the expectation value $E(\theta_A,\theta_B)$ of eq. (L5.9), which is 1 if **A′B** and **AB′** are 0. Your goal is to maximize $E(\theta_A,\theta_B)$ at both wave plate settings.
- In the **Data Taking Parameters** box set **Update Period (Data Run)** to 5 s, and **No. of Samples** to 10, 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 wave plates to the correct angles (corresponding to the polarizer angles given in Q2 above), makes readings, calculates expectation values 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**, **No. of Samples**), and results (*S*, errors, etc.). The **Violations** parameter gives the number of standard deviations by which 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, use more than 5 s per point to decrease the error (the error given is the standard deviation of the **No. of Samples** measurements of *S*). If $S < 2$ you probably need to tweak the state using the wave plate and the birefringent plate in the pump beam. You shouldn't have too much difficulty getting an *S* value of at least 2.3.

L5.7 MEASURING *H*

Now you're ready to perform Hardy's test of local realism.

As discussed above, you'll be measuring the quantity *H*, which depends on several probabilities, all determined by the parameters α and β. Maximum violation of local realism can be achieved using either of the states

$$\left|\psi_1\right\rangle = \sqrt{0.2}\left|H\right\rangle_A\left|H\right\rangle_B + \sqrt{0.8}\left|V\right\rangle_A\left|V\right\rangle_B, \tag{L5.13}$$

$$\left|\psi_2\right\rangle = \sqrt{0.8}\left|H\right\rangle_A\left|H\right\rangle_B + \sqrt{0.2}\left|V\right\rangle_A\left|V\right\rangle_B. \tag{L5.14}$$

We'll start with $\left|\psi_1\right\rangle$, for which the angle parameters are $\alpha = 35^o$ and $\beta = 19^o$. Of course, experimentally it is difficult to produce exactly the state $\left|\psi_1\right\rangle$, so optimal violation may occur for slightly different values of α and β. You'll begin by attempting to produce state $\left|\psi_1\right\rangle$, and assuming $\alpha = 35^o$ and $\beta = 19^o$. The magnitudes of the amplitudes of the states in eqs. (L5.13) and (L5.14) are set by monitoring the coincidence probabilities with the **A** and **B** half-wave plates set at 0°. The relative phase of the states is adjusted by attempting to ensure that $P(-\alpha,\alpha) = 0$.

- Run the LabVIEW program "Hardy-Bell.vi."
- 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°. You'll notice that in the lower right hand portion of the screen, **H HWP Measurement Angles** are displayed. These are the angles that the half-wave plates will need to be set to, in order to measure the four probabilities that comprise *H* [eq. (L5.6)]; they 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 wave plate rotates by θ).

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

By now the pump-beam wave plate and the birefringent plate should be reasonably well adjusted to produce the state $|\psi_1\rangle$. You're ready to take a data run which measures H.

- In the **Data Taking Parameters** box set **Update Period (Data Run)** to 10.0 s, 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 wave plates 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 wave plate, 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.

L5.8 OPTIMIZING YOUR RESULTS

How do 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 three probabilities that 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 or 0.03 for the probabilities you expect to be 0. For a reasonable error measurement you should be using at least 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 at least 10 samples. Increasing the **No. of Samples** parameter will not decrease the error, it will only make the error measurement more accurate (the error is the standard deviation of the **No. of Samples** measurements of *H*). 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. Assuming 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 0.02.

- Rerun the program using a new value for **Beta**.
- Double check the alignment of the pump-beam wave plate and the birefringent plate. With the **A** and **B** wave plates set to 0° adjust the ratio of the coincidences using the pump wave plate; with the wave plates set to measure $P(-\alpha,\alpha)$, minimize this probability with the tilt of the birefringent 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 at least 10 samples.

L5.8.1 Optimization Hints

Don't stress too much about getting $P(-\alpha,\alpha)$ super low by tweaking the pump-beam wave plate and the birefringent plate—it should be down near 0.02 or 0.03, but it's been 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 finish taking data, and then 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 in chap. 8 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?

L5.9 LAST EXPERIMENT

Redo what you've done above using the state $|\psi_2\rangle$ of eq. (L5.14).

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-beam wave plate and the birefringent plate to change the state.** Think about how you'll have to adapt the procedure described above to create the state $|\psi_2\rangle$.

Q12: For the state $|\psi_2\rangle$, 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 may find it useful to redo the lab ticket using the state $|\psi_2\rangle$, and these new values of α and β.

L5.10 References

[L5.1] L. Hardy, "Nonlocality for two particles without inequalities for almost all entangled states," Phys. Rev. Lett. **71**, 1665 (1993).

[L5.2] N. D. Mermin, "Quantum mysteries refined," Am. J. Phys. **62**, 880 (1994).

[L5.3] A. G. White et al., "Nonmaximally entangled states: production, characterization, and utilization," Phys. Rev. Lett. **83**, 3103 (1999).

[L5.4] P. G. Kwiat and L. Hardy, "The mystery of the quantum cakes," Am. J. Phys. **68**, 33 (2000).

[L5.5] J. A. Carlson, M. D. Olmstead, and M. Beck, "Quantum mysteries tested: an experiment implementing Hardy's test of local realism," Am. J. Phys. **74**, 180 (2006).

[L5.6] D. Dehlinger and M. W. Mitchell, "Entangled photon apparatus for the undergraduate laboratory," Am. J. Phys. **70**, 898 (2002); D. Dehlinger and M. W. Mitchell, "Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory," Am. J. Phys. **70**, 903 (2002).

LAB 1

Spontaneous Parametric Downconversion

LAB TICKET

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

L1.1 INTRODUCTION

All of the experiments described here use photon pairs produced via spontaneous parametric downconversion as a light source. This physical process comes in several 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.

In the process of spontaneous parametric downconversion, shown schematically in fig. L1.1, 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 (10s 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). Spontaneous parametric downconversion is said to be "spontaneous" (as opposed to "stimulated") because there are no input signal and idler fields—they're generated spontaneously inside 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

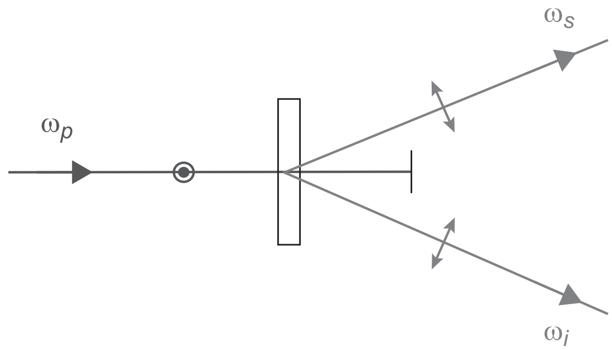

Fig L1.1 Type-I spontaneous parametric down conversion. Inside a crystal one pump photon at angular frequency ω_p is converted into signal and idler photons at angular frequencies ω_s and ω_i. The polarizations of the signal and idler photons are orthogonal to that of the pump.

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 the energy of the pump photon is equal to the sum of the energies of signal and idler photons:

$$\begin{aligned} \hbar\omega_p &= \hbar\omega_s + \hbar\omega_i \,, \\ \omega_p &= \omega_s + \omega_i \,. \end{aligned} \tag{L1.1}$$

We see that energy conservation implies that the frequencies of the signal and idler waves add up to the frequency of the pump. 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:

$$\begin{aligned} \hbar\boldsymbol{k}_p &= \hbar\boldsymbol{k}_s + \hbar\boldsymbol{k}_i \,, \\ \boldsymbol{k}_p &= \boldsymbol{k}_s + \boldsymbol{k}_i \,. \end{aligned} \tag{L1.2}$$

Recall from chap. 2 that the frequencies and wave vectors are not independent of each other; they are related by a dispersion relationship. For the pump wave we have

$$k_p = \frac{n_p \omega_p}{c}, \tag{L1.3}$$

where n_p is the index of refraction of the downconversion crystal at the pump frequency. There are similar expressions for the signal and idler waves.

It is important to note that the indices of refraction depend on the frequency: $n(\omega)$. If the pump, signal, and idler waves are nearly collinear, eqs. (L1.1) and (L1.2) imply that the indices of refraction of all three waves are nearly the same. For most transparent optical materials, the index of refraction increases with frequency in the visible part of the spectrum. Since the pump is at nominally twice the frequency of the downconverted waves, it will ordinarily have a very different index of refraction from the signal and idler. Thus, we need to use a "trick" to satisfy the phase-matching condition. The trick is to use a birefringent downconversion crystal.

In type-I downconversion the polarizations of the signal and idler are determined by the crystal orientation, and are parallel to each other. For maximum efficiency the pump polarization is perpendicular to that of the signal and idler. Since the pump is polarized orthogonal to the signal and idler, in a birefringent crystal its dispersion relationship is different than that of the downconverted beams. For certain crystals it is possible to satisfy the constraints imposed in eqs. (L1.1) and (L1.2) by proper orientation of the pump beam wave vector $\boldsymbol{k}_p$ and polarization with respect to the crystal axes.

The crystal we typically use is β-Barium Borate (BBO). In these experiments the pump laser has a wavelength of around 405 nm, while the signal and idler beams are at 810 nm (twice the wavelength, half the frequency). In order to separate the signal and idler, they are chosen to make a small angle (about 3^o) with the pump beam; 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 (fig. L1.1). 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, e.g., ref. [L1.1]).

However, for a given crystal orientation, there is not a unique solution to the constraints imposed in eqs. (L1.1) and (L1.2). The sums of the frequencies and wave vectors are constrained, but not the individual frequencies and wave vectors. If the idler frequency is somewhat more than half the pump frequency, it is possible for energy to be conserved [eq. (L1.1)] if the signal frequency is an equal amount less. In order for momentum to be conserved [eq. (L1.2)] the idler then makes a slightly greater angle with respect to the pump, and the signal makes a slightly less angle. Thus, the light coming out of a down conversion crystal is emitted into a range of angles (up to a few degrees), and wavelengths (on the order of 10s 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. (L1.1) and (L1.2). It is also the case that these photon pairs are emitted at the same time (to a very high precision), and 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 these experiments) we say that they are coincident, and assume that they constitute a signal-idler pair.

In Lab 1 we'll be exploring things like the momentum conservation rule and the precision of the timing of the photon pairs. The experimental apparatus is shown in fig. L1.2. The signal and idler photons are collected with lenses, coupled into optical fibers and directed to single-photon counting modules (SPCMs) 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 SPCMs. These are RG780 filters that block wavelengths shorter than 780 nm, and transmit wavelengths longer than this. Their purpose is to transmit the downconverted light, while blocking scattered blue pump light and the green safe light used to illuminate the laboratory.

The SPCMs output an electrical pulse every time they detect a photon. These pulses then go the coincidence-counting unit (CCU). The CCU takes inputs from up to four detectors, and uses a programmable logic chip (a field programmable gate array, or FPGA) to implement the coincidence logic and eight counters. In the labs described here, four of the counters count the pulses coming directly from the individual SPCMs (called singles counts), while the other four register 2-, 3-, or 4-fold coincidence counts.

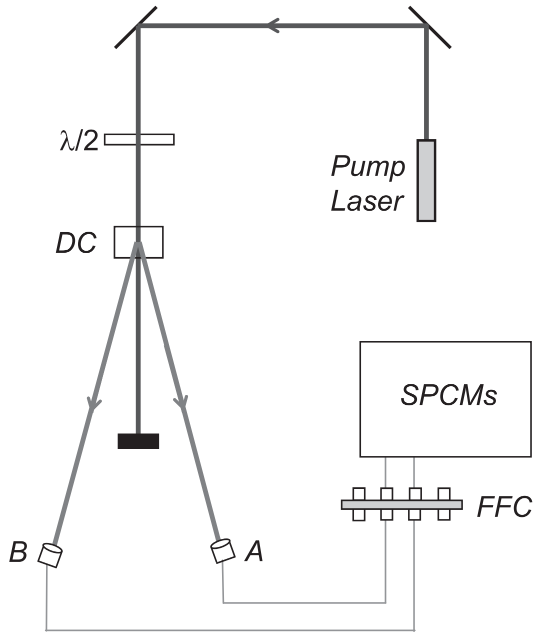

Fig L1.2 The experimental apparatus. Here λ/2 denotes a half-wave plate, DC denotes the downconversion crystal, FFC denotes fiber-to-fiber coupler, and SPCMs denotes the single photon counting modules. The signal and idler beams impinge on the collection optics A and B, are focused into fibers, and delivered to the SPCMs.

Your instructor will show you how to configure the CCU to obtain the proper coincidence signals. Data from the counters is streamed from the CCU to the host computer.

An important 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 detector-**A** (for example), but really we mean aligning the lens and optical fiber that deliver the downconverted light to the detector. Figure L1.3 shows the mounts, lenses, and fibers of the signal and idler light collection optics. 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.

L1.2 ALIGNING THE CRYSTAL

Note to instructors: I would suggest that the crystal alignment described in this section be performed prior to students coming into the laboratory. You can then remove the detectors so that the students can align them, beginning with the procedure presented in sec. L1.3.

The pump laser should be mounted so that its polarization is vertical (or horizontal). The beam must be aligned so that it is approximately collimated and traveling level to the table at a convenient height (4 inches or so). It is also useful if the beam is traveling directly above a row of holes in the optical table or breadboard. If your laser is not pre-collimated, you'll need to insert a collimation lens. The beam can be leveled and directed along a row of holes using the two mirrors shown in fig. L1.2. Once the beam

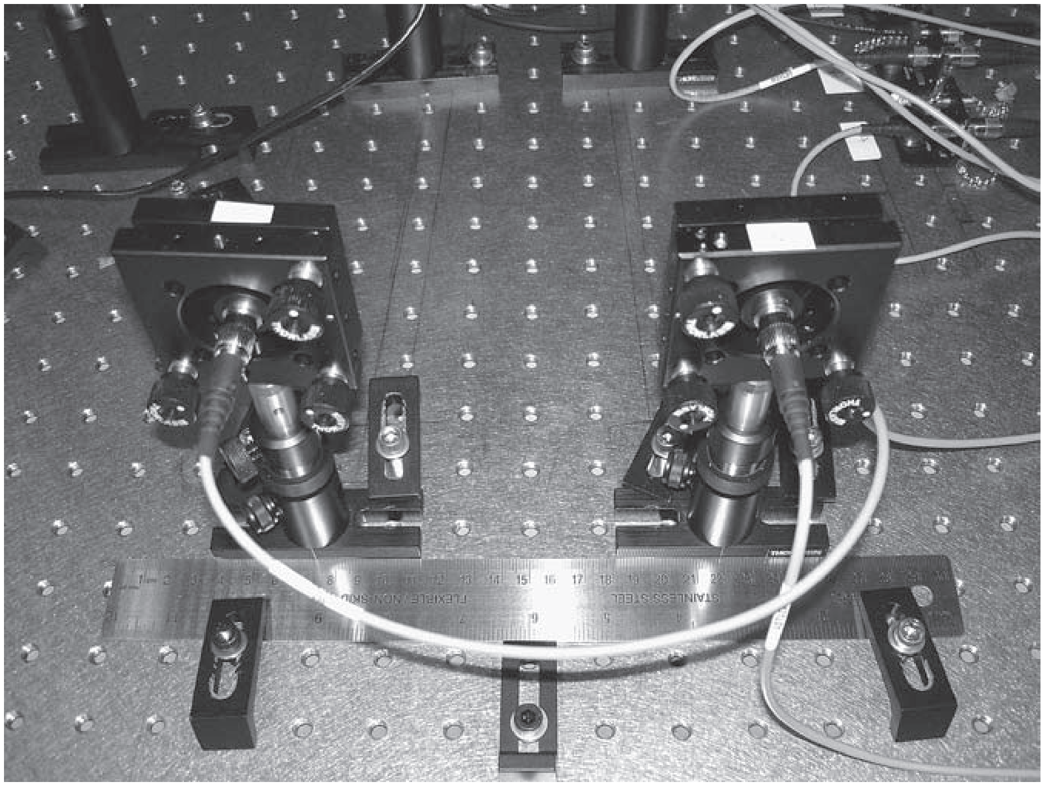

Fig L1.3 The fiber-coupling mounts.

has been leveled, it serves as a convenient reference that will allow you to place other optics, such as the fiber coupling-lenses, at this same height.

The crystal alignment proceeds as follows:

- **Double check that the detectors are turned off.**
- Insert the 405 nm half-wave plate and the downconversion crystal into the pump beam. Orient them so that they are perpendicular to the beam. This is most easily done by looking at the back reflection from the optic, and making sure that this reflection travels nearly along the direction of the incoming beam. Rotate the half-wave plate so that it is at 0°.
- Use the alignment laser to coarsely align detector-**A**, as described below in sec. L1.3. When this is done, make sure that the alignment laser is turned off, and then disconnect the **A**-fiber from the alignment laser, and connect it to the fiber leading to the **A**-detector SPCM.
- Run the LabVIEW program "Coincidence.vi" (some of the basics of this program are discussed in sec. L1.3, and more details are given in the documentation that came with the program).
- **Make sure the room lights are turned off** (it's OK for the green safe lights to be on) and turn on the detectors.
- Adjust the horizontal and vertical tilts on the mount holding the detector-**A** collection optics to maximize the count rate.

At this point you will hopefully see a large number of counts on detector-**A**, but you need to make sure that these counts are actually downconversion and not just background.

- Rotate the half-wave plate in the pump beam while observing the counts on detector-**A**. As the wave plate is rotated the counts should increase and decrease; this dependence on the pump polarization is confirmation that you are seeing downconversion. Rotate this wave plate to maximize the number of counts on detector-**A**.

If you do not see a dependence on the polarization of the pump, you are not seeing downconversion. There are two possibilities: (1) Detector-**A** is not properly aligned, so you need to go back and realign it. (2) Your crystal is possibly too far away from the correct tilt angle, so skip the next bulleted step, and then continue following this procedure. You may need to iterate back-and-forth between adjusting the pump polarization and the crystal tilt in order to see downconversion.

- Perform the fine alignment of detector-**A** described below in sec. L1.3, sliding the collection optics along the ruler to optimize the angle that the signal beam makes with the pump beam.

At this point the crystal should still be perpendicular to the pump beam; now you want to optimize its tilt angle. Your crystal can be tilted by using the adjustment screws on its mount. The downconversion efficiency will be extremely sensitive to tilt in one direction (horizontal or vertical), but very insensitive to tilt in the other. Which direction is sensitive depends on the orientation of your crystal, and the pump polarization: For a vertically polarized pump, the crystal should be sensitive to tilt in the vertical direction.

- Using the adjustment screws on the crystal mount, slowly tilt the crystal horizontally, while monitoring the counts on detector-**A**. If the count rate is sensitive to this tilt, adjust the tilt to maximize the count rate. If the count rate is insensitive to this tilt, adjust the crystal so that it is perpendicular to the pump.
- Repeat the last step while adjusting the vertical tilt.

Your downconversion crystal should now be reasonably well aligned. When you have completed the full alignment of both detectors, described below, you might want to once again carefully adjust the tilt of the crystal in order to maximize the coincidence count rate.

L1.3 ALIGNING DETECTOR A

The downconversion crystal is cut so that when properly aligned, the signal and idler beams make nominal 3° angles with respect to the pump beam. 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.

- **Double check that the detectors are turned off.**
- **Insert a beam block in the blue pump beam.**

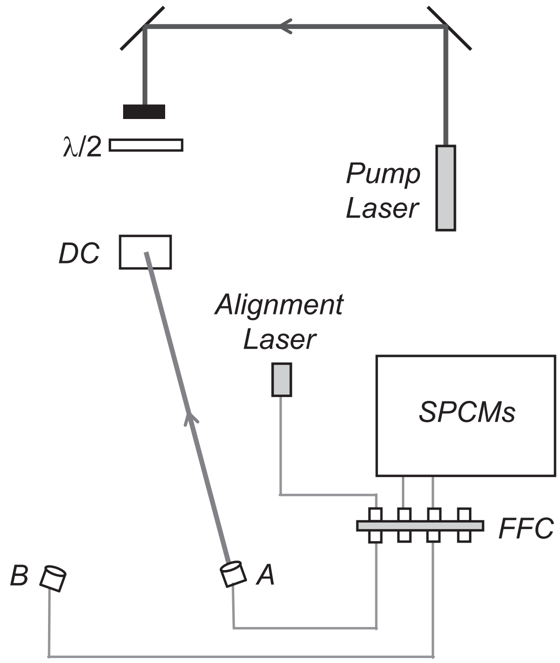

Fig L1.4 Using the alignment laser. The beam should travel backward from the collection optics, and onto the downconversion crystal.

- The fiber from the **A** collection optics leads to a fiber-fiber coupler, where it joins another fiber which leads to the filters and a SPCM. Unscrew the fiber coming from the **A** collection optics, and connect it instead to the fiber leading from the alignment laser, as shown in fig. L1.4. **Please do this carefully,** so that you don't scratch the fiber tip.
- Place the detector-**A** mount 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. L1.3).
- Turn on the alignment laser (**your instructor will tell you the maximum current for your laser**), 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 that your eye is not very sensitive to.[1] If you stick white paper in the beam, you should be able to see it when the room lights are out. You should also be able to see it very easily using a CCD camera and a monitor.
- Gently screw the **A**-detector mount to the table, and double check that the laser is still shining on the center of the crystal.
- **Turn off the alignment laser.**

1 The alignment laser puts out several milliwatts of light at about 800 nm. Your eye is not very sensitive to this light, but it IS a fairly intense beam, and you should **be careful not to look directly into it.** Also, **take care not to accidentally couple the laser light into the fiber leading to the SPCMs.** The filters will not block much light at this wavelength, and the SPCMs are VERY sensitive to it and could easily be damaged. It is wise to **make sure that the SPCMs are turned off while the alignment laser is turned on**.

- Unscrew the **A**-fiber from the alignment laser, and connect it to the fiber leading to the **A**-detector SPCM. Take care when you do this.

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

- Start by opening the LabVIEW program “Coincidence.vi”.
- 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.

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.

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 as you want them to be, you press the **Take Data** button and the program switches to data record mode, in which 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 possibly 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 (highlight the value at the top, and replace it with a new value). The idea is that you’re going to be trying to increase the **A** count rate, so you want to have some room on the display to see the count rate increase.
- Slowly adjust the horizontal tilt of the detector-**A** mount while observing the count rate. If tilting in one direction decreases the counts, tilt the other way. Keep tilting 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 detector-**A** (using the ruler as a guide) and the count rate.
- While holding the mount in place with one hand, and keeping it pushed against the ruler, unfasten the screw that secures the mount to the table. Using one hand to hold 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, but you can adjust it if you do need to.
- Slide the detector mount 0.5 or 1 mm in either direction, and readjust the tilt to maximize the **A** detection rate. Note 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.
- Once the count rate is maximized, 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?

L1.4 ALIGNING DETECTOR B

The idea now is to place detector-**B** 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. (L1.2). Since detector-**A** is now fixed, it is necessary to place detector-**B** in the correct spot to properly detect the photon pairs. 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.
- Connect the fiber from the collection optics for detector-**B** to the alignment laser at the fiber-fiber coupler (similar to fig. L1.4, but with **B** connected instead of **A**).
- Place the detector-**B** mount so that the base pushes the up against the ruler, as shown in fig. L1.3. Begin by locating detector-**B** so that it makes roughly the same angle from the pump beam as detector-**A**.
- Turn on the alignment laser, and adjust the tilt of the mount so that the beam shines onto the downconversion crystal in order to coarsely align detector-**B**. 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 SPCM **B**.

- Remove the beam block from the blue pump beam.
- **Make sure the room lights are turned off,** and then turn on the detectors.
- Slowly adjust the horizontal tilt of detector-**B** 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. If you do not see any coincidences, or just very few coincidences, you can start by simply maximizing the singles count rate on detector-**B**.
- Repeat the last step, but using the vertical tilt adjustment.
- In your lab notebook, record the position of detector-**B**, and the **B** and **AB** detection rates.

Now perform the fine alignment of detector-**B**.

- While holding the **B** mount in place with one hand, and keeping it pushed against the ruler, unfasten the screw that secures the mount to the table. Using one hand to hold 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.
- Now repeat the procedure you did before, but with detector-**B**. 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. Ask your instructor what count rate you should be shooting for.
- Once the count rate is maximized, carefully screw the mount securely to the table, then give one final adjustment of both the vertical and horizontal tilts.
- Record the position of detector-**B**, 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?

L2.3 ALIGNING THE IRISES AND THE BEAM SPLITTER

In lab 1 you examined the behavior of a spontaneous parametric downconversion source. You learned how to maximize the coincidence count rate between detectors **A** and **B**, and here we will assume that this part of the alignment has already been completed. Your task in this lab will be to insert a beam splitter in the signal beam, and to align detector **B′**. Once this is done you'll be able to measure $g^{(2)}(0)$.

- **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. L2.3. **Take care when you do this.**
- Turn on the alignment laser. 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. L2.3.[5] 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 a CCD camera and monitor. If the laser light is not shining onto the downconversion crystal, detector-**B** is not properly aligned, and you'll need to complete this alignment (see lab 1) before continuing.

4. You may be surprised that a classical field having a very low photon flux, such as a highly attenuated laser, cannot give $g^{(2)}(0)=0$. However, as described in chapters 12 and 16, the light from a laser is described quantum mechanically by a "coherent state." No matter how highly attenuated it is, even to the level of just one photon per second or less, there is always a nonzero probability for laser light to contain two or more photons. This means that $N_{BB'} \neq 0$, allowing $g^{(2)}(0)=1$ [eq. (L2.10)].

5. Recall that the alignment laser puts out several milliwatts of light at about 800nm. This light can be dangerous to both your eyes and the SPCMs, so use care.

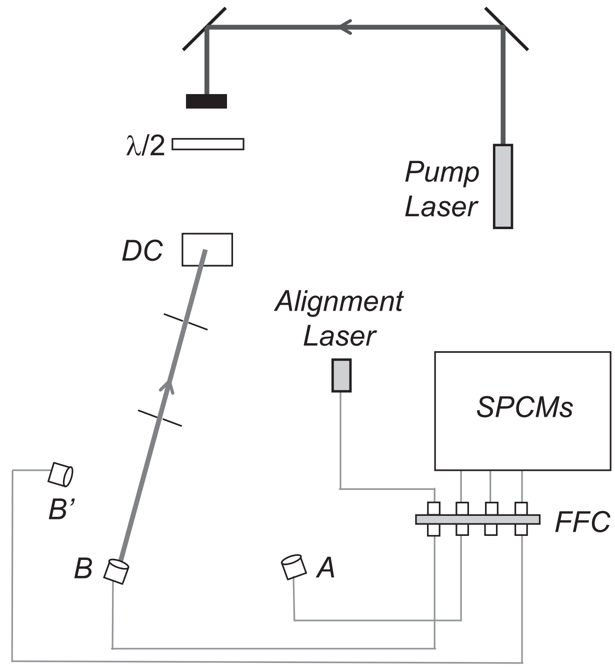

Fig L2.3 Aligning the irises.

- First you want to center two 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 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 2–3 mm 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.
- Insert the polarizing beam splitter (PBS) about 3–4 inches away from the **B** collection optics (fig. L2.2). Make sure it is oriented so that light coming from the downconversion crystal will be reflected away from the beam going to detector-**A**. Make sure that the beam passes through the center of the beam splitter.
- Orient the beam splitter so that its face is perpendicular to the beam. Do this by looking at the back-reflection from the beam splitter, which shines back toward the collection optics (this beam will be VERY dim, so you will probably need the CCD camera to see it). Orient the beam splitter so that this back-reflection goes straight back on top of the incident beam. Double check that the beam is still centered on the beam splitter, then screw the beam splitter mount to the table.
- Insert the half-wave plate between the PBS and the downconversion crystal, about an inch or two from the PBS. Again, center it, orient it perpendicular to the beam, and screw it to the table.

L2.4 ALIGNING THE B′ DETECTOR

You will be aligning the **B′** detector so that it collects light from the same beam as the **B** detector.

- Place the mount with the **B′** collection optics on the reflection side of the beam splitter, about an equal distance from the beam splitter as the **B** collection optics (fig. L2.2). Don't screw it down yet.
- Unscrew the **B**-fiber from the alignment laser, and reconnect it to the fiber leading to SPCM **B**. Connect the **B′**-fiber to the alignment laser, as shown in fig. L2.4. 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 with the **B′** collection optics sideways (perpendicular to the beam), rotating it, and adjusting its 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 sideways to center the beam on the first iris (closest to the beam splitter). Adjust the tilt of the mount 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 beam splitter.

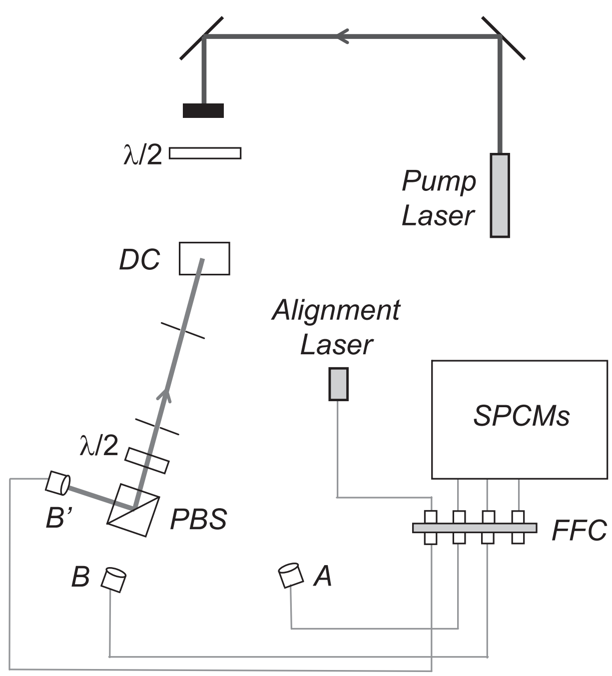

Fig L2.4 Aligning detector-**B′**.

- Adjust the vertical and horizontal tilt of the beam splitter 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 beam splitter 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 SPCM **B′**.
- Run the LabVIEW program "Coincidence.vi".
- Set **Experimental Setup** to **g(2) 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.
- **Make sure that the lights are out**, and then turn on the detectors. Open the irises wide, and unblock the blue pump beam.
- Slowly rotate the wave plate in front of the beam splitter while monitoring the count rates. You should notice that for some wave plate 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 wave plate to maximize the **AB** counts. Adjust the tilt on the **B** mount to maximize this coincidence rate.
- Rotate the wave plate 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 approximately the same (hopefully within 10–20%). If this isn't the case, there are a few possible problems. The first is that either detector-**B** or **B′** is not well aligned. You can try tweaking the alignment to improve things, but you might need to go back and realign. Other possibilities are that the fiber coupling lens is better aligned for one of the detectors than the other, or the end of one of the fibers has dirt on it. If you get drastically different maximum count rates for **AB** and **AB′**, ask your instructor what you should do.

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

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