

Lab 2 Spontaneous Parametric Down Conversion and State Projection

Week 2

Phys434L Quantum Mechanics Lab
2021

February 20, 2021

1 The Overall Picture

As mentioned in the previous lab write-up, our laboratory setup consists of preparing photon pairs. In this process, a pump photon of energy E_p is converted into two photons of energy E_1 and E_2 such that

$$E_p = E_1 + E_2, \quad (1)$$

or expressed in terms of the wavelength in vacuum via $E = hc/\lambda$,

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}, \quad (2)$$

In a birefringent medium, spontaneous parametric down-conversion occurs due to the interaction of the light and the medium. For down-conversion to occur, momentum must be conserved:

$$\vec{p}_p = \vec{p}_1 + \vec{p}_2. \quad (3)$$

If the down-conversion photons have the same energy, then they come out at equal and opposite angles from the original direction of the parent photon. The two photons are produced simultaneously from a parent photon. In this experiment we use this method to “herald” a photon that is subject to quantum operations. Another way to think about it is that we use one photon to “tag” the other photon. Then we detect both and measure the detections in coincidence to make sure we are detecting only photons with a partner. It is a way so make sure we are doing an experiment with single photons.

In this lab’s setup we use 3 detectors. One photon gets detected by only one detector we call Alice. The other photon can be detected either in the straight-through direction if it is horizontally polarized, by a detector we call Bob, or in the reflected direction if it is vertically polarized, by a detector we call Charlie. The photons actually get channeled into optical fibers that take them to corresponding detectors. The detector signals are

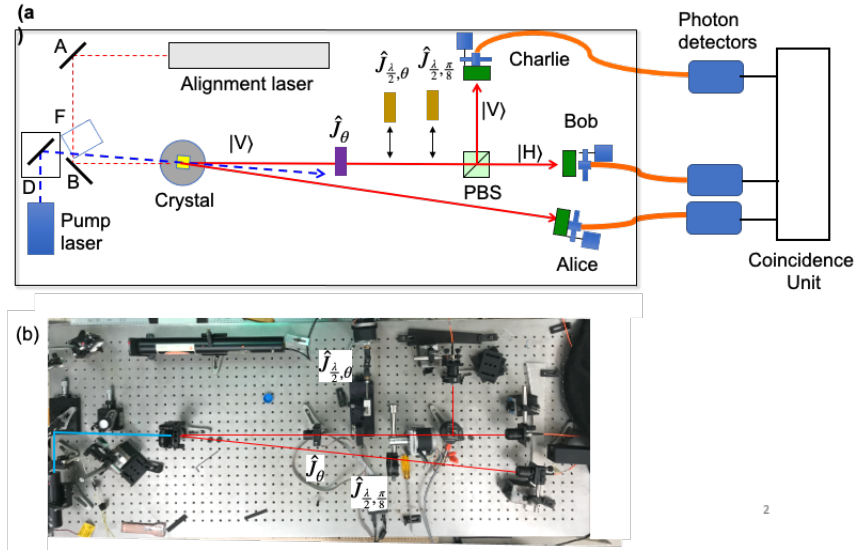


Figure 1: Basic setup of the apparatus. (a) Schematic; (b) Photo.

processed by a coincidence unit. The device that diverts the photons by polarization is called a polarization beam splitter. Thus the polarizing beam splitter in conjunction with Bob and Charlie act as a polarization analyzer.

The photon heading to the polarization analyzer is initially vertically polarized. It first encounters a polarizer, whose axis orientation we can control (\hat{J}_θ). We can also “slide” in a half-wave plate whose axis we can also control ($\hat{J}_{\frac{\lambda}{2}, \theta}$). Finally before the polarization beam splitter we can rotate a half-wave plate with axis at 22.5 degrees ($\pi/8$) ($\hat{J}_{\frac{\lambda}{2}, \frac{\pi}{8}}$). This in combination with the polarization beam splitter acts as a polarization analyzer in the 45 basis.

So we have several controls at our disposal:

- We can block/unblock the pump laser via the Arduino program.
- We can turn on/off the power to the detectors via the Arduino program.
- We can block/unblock the alignment laser so you can see the path of the down-converted photons heading to the polarization analyzer. We can only do this while the detectors are off. We do this via the Arduino program.
- We can rotate the transmission axis of the polarizer P_θ via a serial-port command.
- We can slide in or out a half-wave plate. This motion is controlled by a Teensy program. We can control the axis of the wave plate via a serial port command.
- We have a fixed waveplate mounted on a mount that can rotate it in or out of the path of the photons. This is also controlled by the Teensy program.

- We record the photons that are detected by Alice, Bob and Charlie. We can also record the coincidences between Alice and Bob and between Alice and Charlie. We do this with a Matlab program.

2 The Remote Apparatus

2.1 General

You will log into the lab computer using remote desktop. Once you do this, your screen will appear as something like what you see in Fig. 2. You will see 5 windows. One is a view of the apparatus from a webcam (center in the photo). The window on the upper left is a serial interface to the Arduino based circuit that has three functions: To block/unblock the (blue) pump laser, and to turn ON/OFF the power to the detectors, and block/unblock the (red) alignment laser (more on this below). On the lower left is a Teensy window that controls the positioning of two half-wave plates, one via a linear stage and another one via the rotation of an arm holding it. The lower two windows are serial controls for the rotating elements: the polarizer and the sliding half-wave plate. On the right is a window with the Matlab platform that is used to record the data from the 3 detectors.

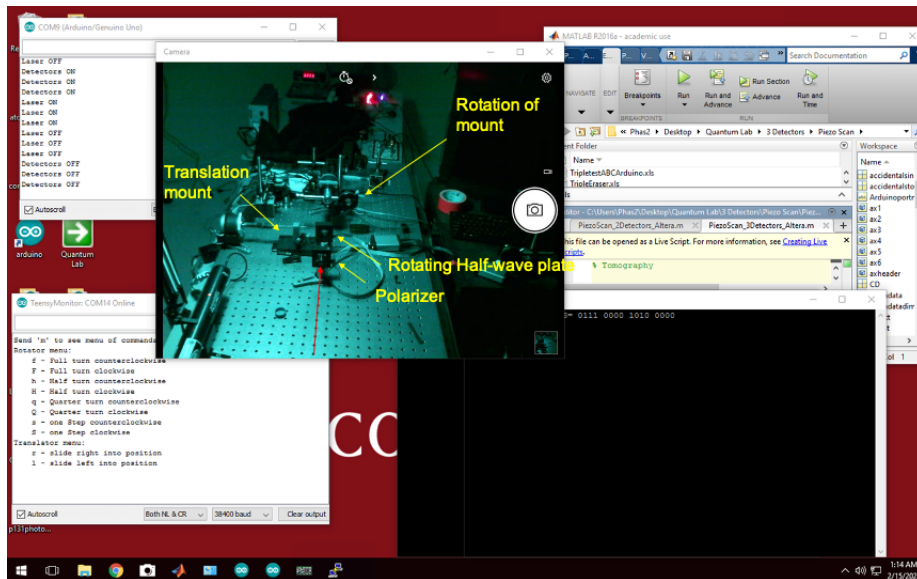


Figure 2: Screen of the Desktop that controls the experiment in the lab. It has a webcam window (center), an Arduino interface window (upper left), a Teensy interface (lower left) two serial interface windows (lower center) and a Matlab window (right).

2.2 Commands

Here we detail the commands for the different programs. All commands given below are within quotation marks. **Do not enter the quotation marks.**

2.2.1 Logging in

You log into the lab computer using remote desktop. The address of the PC is:
Ho313-96143W.colgate.edu

Then you log into the PC:

Username: phas2

Password: Fr2=Gm1m2

2.2.2 Arduino Interface

This action is for providing safety in the lab. The laser (class IV) is always on, but that creates a safety issue, so the laser beam is blocked. Turning the laser on/off does not work well because there is a warm-up time for which the laser is unstable and its wavelength drifts, so the laser is left on and the beam is blocked or unblocked, as shown in Fig. 3. The laser blocker and detector power are controlled by a program that runs on an Arduino/Teensy circuit (in case you know what this is). We have this option for the 3 detectors (Alice, Bob and Charlie) because they are very sensitive and so it is better to turn them off when not in use. Because we have a moving parts, we have an option for a better view of the alignments: to unblock the alignment laser. However, the detectors must be off when this laser is on.

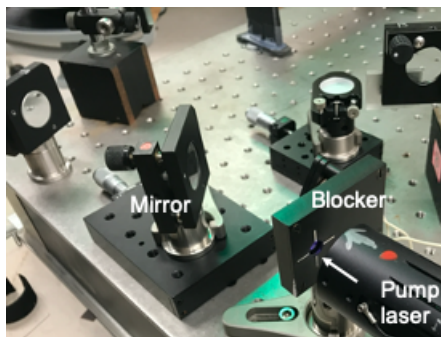


Figure 3: Photo of the pump laser and beam blocker.

The Arduino program is always running. A serial window is shown in the figure. The command is entered on the top command line. The action taken is listed in the lower part of the window. A summary of commands is:

- **Pump Laser ON (Unblocked):** On the command line type “1” . Turn it on before you start the experiments. You can do two visual verification that the beam is hitting the polarizer mount.

- **Pump Laser OFF (Blocked):** On the command line type “2” . Turn it off once you are done with the lab session.
- **Detectors ON:** On the command line type “3” . Turn it on before you start the experiments. There is a green LED that is turned on when the detectors are connected to the power supply. There is also a red digital readout near the top-central part of the webcam window that indicates how much voltage is being applied to the detectors. This voltage should be close to 5 V. The value should be slightly above 5 V but never below 4.5 V (otherwise the detector signals will be unstable).
- **Detectors OFF:** On the command line type “4” . Turn it off once you are done with the lab session.
- **Alignment Laser ON (unblocked):** On the command line type “5”. **Before you do this you must be sure that the detectors are off:** the digital display seen with the webcam must read 0.000.
- **Alignment laser OFF (blocked):** On the command line type “6”.
- **Cold Restart:** In case you need to do this, in the command bar there is a round icon for the Arduino platform. You click on this. Then you click a right arrow in the upper left that compiles the program and loads it to the circuit. You then need to go to the top menu bar, click “Tools” and then click “Serial Monitor.” This opens the screen that you see in the figure. Resize it and put it in the lower left. You can then minimize the Arduino platform.

2.2.3 Teensy Interface

This interface controls the placement of two half-wave plates: the rotation of the fixed-axis one, in and out of the path of the photons; and the translation of a rotatable-axis one in and out of the path.

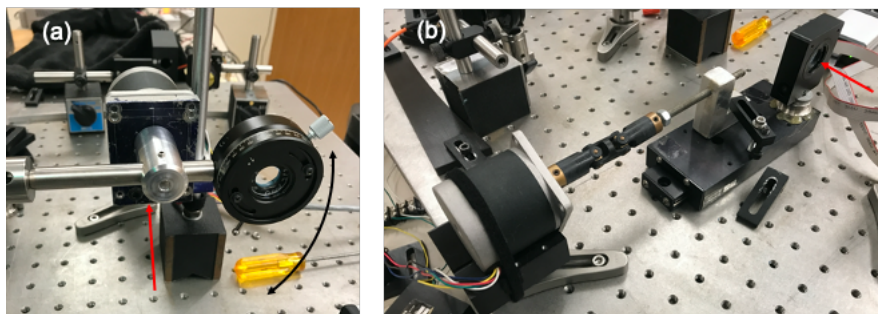


Figure 4: Photo of (a) the rotation hardware for the fixed-axis wave plate, and (b) the translation hardware for the rotatable-axis wave plate. Straight arrow shows the path of the photons.

There are several commands for each:

- **Menu:** Type “m” for a menu of the options.
- For the fixed-axis wave plate:
 - “h” for half-turn counter-clockwise.
 - “H” for half-turn clockwise.
 - “q” quarter-turn clockwise.
 - “s” one step counter-clockwise.
 - “S” one step clockwise.
- For the rotatable-axis wave plate:
 - “r” to slide right into path.
 - “l” to slide left into path.

2.2.4 Serial Interfaces

2.2.5 Rotational Controls

We have 2 rotational mounts controlled by serial interfaces (the ones with a black background). The one labeled “Polarizer” controls the rotation of the transmission axis of a polarizer, as shown in Fig. 5(a). The one labeled “Half-wave plate” controls the rotation of the axis of the waveplate, shown in Fig. 5(b).

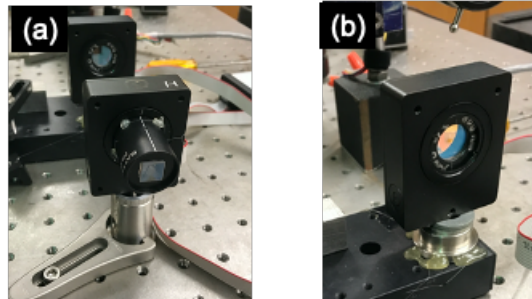


Figure 5: Photo of the motorized rotation stages: (a) polarizer and (b) half-wave plate.

The way to move the motor is to enter “ma” followed by the angle in degrees times 9 (i.e. in “nods,” so 10 degrees is 90 nods, and 90 degrees is 810 nods). Once you enter the command, a line-record of the instruction appears. This is also useful to keep track of what was the previous instruction. It is important to verify that the rotator is moving. There is a small mark on the of the optical element.

2.3 Matlab Interface

This is the standard Matlab platform that we use to take data. We will use two programs:

- **PiezoScan_3Detectors-Altera**

This program does a scan of a voltage variable. However, for this lab it is not connected to anything, so the scan is effectively a scan over time. When you run it you are asked to fill-in a menu, shown in Fig. 6(a):

- **COM Port of Counter:** Must read read “COM6”
- **COM Port of Arduino:** Must read read “COM13”
- **Start Voltage:** Usually 1
- **End Voltage:** Usually 8 (can be lower but not higher)
- **V increment:** Usually 0.05. Determines the number of points: $(8-1)/0.05 = 140$ points. If you want a specific number of points N , then

$$V_{\text{increment}} = \frac{V_{\text{end}} - V_{\text{start}}}{N} \quad (4)$$

- **Time interval:** Time per point. Usually 1 s
- **Excel File Name:** Enter the name of the file. Usually the group name and experiment number.

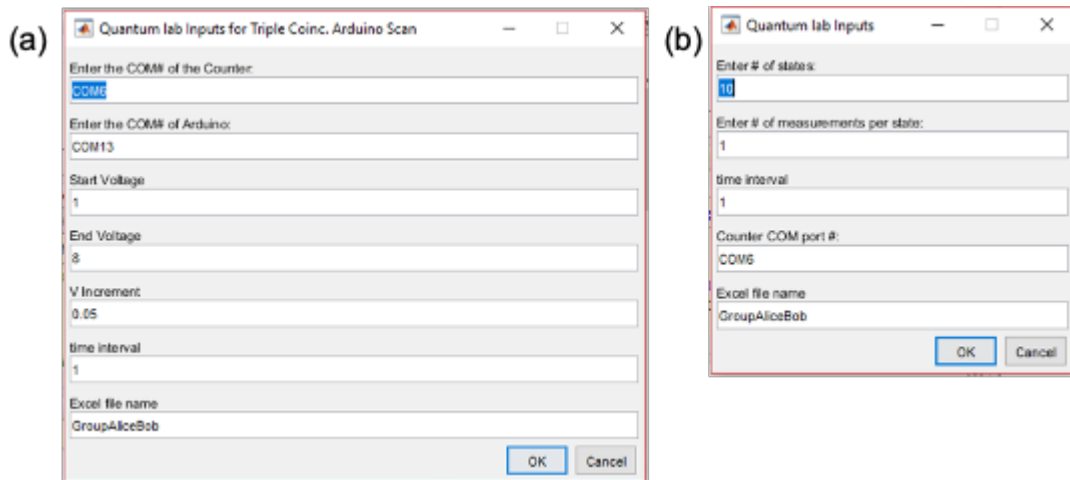


Figure 6: Photo of the Matlab menus: (a) Scanned and (b) Stepwise paused.

- **Paused_3Detectors-Altera**

This program does a stepped scan displaying a specified number of points. It pauses in between points so that you can change the waveplate or polarizer angles. A menu will appear with several entries (see Fig.6(b)):

- **COM Port of Counter:** Must read read “COM6”
- **Number of states:** This is the number of measurements you need. You get a pause between measurements
- **Number of measurements per state:** This is number of measurements per pause. Normally set to 1.
- **OK button:** The program will take a data point after you click this, and then pause once it is ready to take another point.
- **Excel File Name:** Enter the name of the file. Usually the group name and experiment number.

3 Experiments

This lab continues the alignment done the previous lab, where all components were put in place aligned with the alignment beam. In this lab we will do experiments with single photons to investigate the properties of quantum mechanics algebra. You will require to do a group lab write-up for this experiment. Members of the group should divide tasks, but all should do the theory part individually. The first step in this experiment is to set up the apparatus to produce spontaneous parametric down conversion. At least one group member should keep detailed notes of what you do in a bound notebook (not loose sheets nor in a random piece of paper).

3.1 Experiment 1: An Overview of the Apparatus

- **Task 1: Inspection** This is a good point for making a sketch of the apparatus in your notebook and adding by hand all the details that you can think.
- **Task 2: Getting to know all the controls: A walk-through**
 1. Unblock the alignment laser via the Arduino interface by typing “5”. You should see the scattering of the laser from the optical components. (You can expand the webcam view to see better.)
 2. Rotate the fixed wave plate via the Teensy interface. For example, enter “Q” to put the waveplate into position (the lower position- you will see the laser scattering from it when it is in position). You can enter “q” to return it back to be out of position.
 3. Slide the rotating wave plate into position by entering “r”. You will see it move, taking about 1 minute to complete.
 4. Block the alignment laser via the Arduino interface by typing “6”. You should no longer see a red glare reflected from the optical components.

5. Next unblock the pump laser by entering “1” in the Arduino interface. You will see the glare of the purple-colored laser beam hitting the frame of the polarizer. At this point down-converted photons are being produced.
6. Turn-on the detectors by typing “3” in the Arduino interface. You will see the red digital display in the webcam view read approximately 5 volts.
7. Now let’s go to the Matlab interface. Run the Scanning program “PiezoScan_3Detectors-Altera”. Follow the instructions given in Sec. 2.3. Use the suggested parameters. You will see data points in 6 screens A=Alice, B=Bob, C=Charlie. You will also see the coincidences AB and AC in the bottom left and center, respectively. The window in the lower right is ABC, the triple coincidence, which should be near zero. We will get into it next lab.
8. At this point you will see counts recorded in each graph. Rotate the polarizer to 45 degrees. The polarizer is already rotated 90 degrees so that the input photons in state $|V\rangle$ can get through. In Sec. 2.2.4 we indicated that the angle has to be entered in nods (ninth of degrees), which for this operation equals $45^\circ \cdot 9 = 405$ nods. So in the serial interface called “Polarizer” enter “ma405”. You should see it move in the webcam. See the data change. Can you explain it? You can change the polarizer to other angles as well. No damage is done for trying. If the scan runs out, just repeat it.

By now you may have encountered the annoying feature that the Matlab GUI takes up the whole screen blocking the other menus. You can change its size by clicking on the frame.

9. Once you are done playing with the polarizer, put it back to 90° via “ma810”.
10. Now let us rotate the wave plate that was slid into position. Go to the serial interface called “Half-wave plate” and type “ma203” this rotates the wave plate to approximately 22.5° . rotating the state of polarization to be $| -45 \rangle$. **The angles are measured looking into the beam.** The webcam’s view is with the beam.

In your notebook record what you did and what you observed.

- **Task 3: Statistics.** Record a fresh new scan. The coincidence counts of the two detectors must be larger than the accidental coincidences, given by

$$N_{\text{acc}} = N_1 N_2 \Delta T, \quad (5)$$

where N_1 and N_2 are the singles counts per second and ΔT is the maximum time delay between pulses that is considered a coincidence. For example, a typical coincidence circuit has $\Delta T = 50$ ns. If the singles are $20,000 \text{ s}^{-1}$ for each detector, then we should expect an average of 20 accidental coincidences per second.

Question 1 Calculate the accidental coincidences for your signals and compare them with the measured coincidences.

Question 2 You can consider the statistics to be Poissonian, and so the error in the number of recorded counts N , is \sqrt{N} . Take the average and standard deviation of the individual counts that you record and compare with \sqrt{N} .

3.2 State Transformation and Detection

The setup for this experiment is shown in Fig. 7

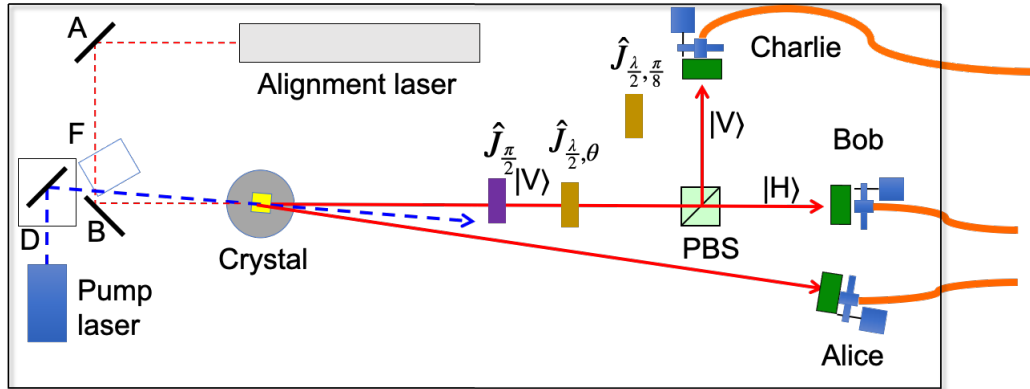


Figure 7: Using a Polarizing beam splitter (PBS) to deflect photon path by polarization (horizontal going straight to Bob, and vertical deflected toward Charlie). The state is transformed by a half-wave plate ($\hat{J}_{\lambda/2, \theta}$).

The important pieces of equipment are:

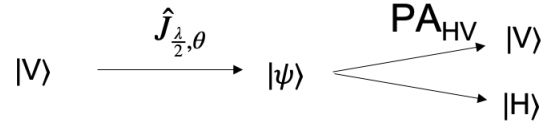
Qty	Part	Description/Comments
1	Polarizing beam splitter	Mounted
1	Fiber collection assembly.	(DC) Multimode fiber with FC type connectors, mounted collimator plus concentric iris mounted on the collimator mount.
1	Band-pass filter	800-810 nm center, 40-nm bandwidth.
3	Detector.	Avalanche photodiode, fiber-coupled.
2	Half-wave plate	Mounted and calibrated.
1	Polarizer	Glan-Thompson type. Mounted and calibrated.

Note: All positive angles are measured relative to the horizontal, for counter-clockwise rotations when looking into the beam.

3.2.1 Prediction

The gist of the setup is the following: Down-converted photons are produced in state $|V\rangle$. The polarizer is now with its axis vertical, preserving this state. The photons are then

incident on a half waveplate that can be at an angle that you specify, and finally the photons are measured in the HV basis.



We can measure the photons that arrive to Bob and Charlie. From them we can extract the fraction of the totals, which can be compared to probabilities.

Question 3 What is the probability of measuring the photon in states $|H\rangle$ and $|V\rangle$ for the waveplate at an angle θ ?

Recall that the half-wave plate has an operator given by

$$\hat{J}_{\lambda/2, \theta} \doteq \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \quad (6)$$

3.2.2 Making Measurements

- **Task 4: Normalization:** The role of the polarizing beam splitter followed by the detector is to do measurements on the HV basis. If N photons are incident on the beam splitter in state $|\psi\rangle$ then $N_H = NP(H/\psi)$ are transmitted, and $N_V = NP(V/\psi)$ are reflected.

Record the average number of counts when the wave plate angle $\theta = 0$ and $\theta = 45^\circ$. Call these $N_{V_{\max}}$ and $N_{H_{\max}}$. We will use these to normalize the counts in other sections of the lab.

- **Task 5: Taking data:** Now your role switches to experimenter. You have a prediction. Take measurements to test that prediction. Your probabilities are in terms of θ , and you can vary θ . We have another program called “Paused_3Detectors_Altera” that takes data in a step-wise fashion. So you could take data by varying θ over some range that you must decide, and in increments that you judge are sufficient. (You will be graded on these decisions.) Once you calculate your range and step size, calculate the number of data points you will have. You enter the number of points in the menu that appears when you run the program (see Sec. 2.3), adding a few extra points just in case. Record the date and time of your data run. The program saves the scan in an Excel file with date and time labeling the sheet tab. You can do several trials with a smaller number of points if you wish. All get recorded. Name the Excel file according to some file-naming system you devise.

Question 4 For your report: Graph $N_V/N_{V_{\max}}$ vs. θ , plotting also the error bars that go with each point (\sqrt{N} , and propagating errors), and plot it against the calculated probability in $P(V/\psi)$. Do a second similar plot for the data for $N_H/N_{H_{\max}}$

and the calculated $P(H/\psi)$. Display them in the same graph. Are they what you expect?

3.3 Polarization Projection

We now want to verify state projection by a polarizer.

- **Task 6: Slide the wave plate out:** In the Teensy interface you type “1”. The apparatus should look like the one shown in Fig. 8

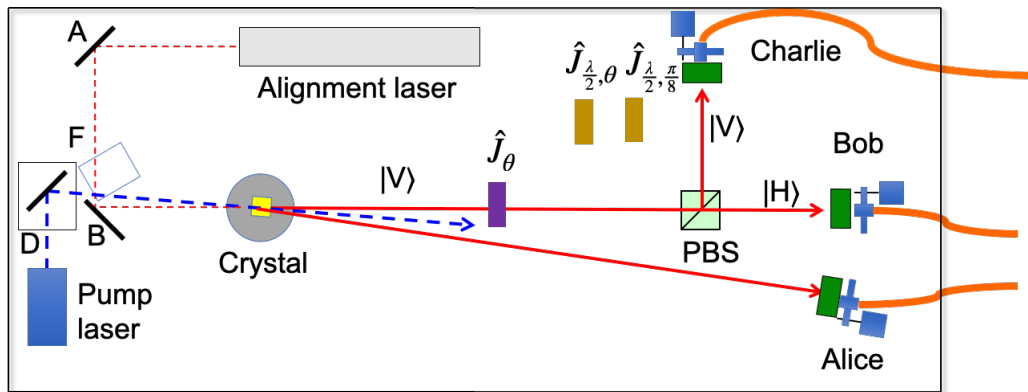
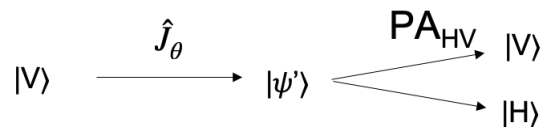


Figure 8: Apparatus for studying the state-projecting effect of the polarizer.

3.3.1 Prediction

Now consider the following situation. The input photon is in state $|V\rangle$. It encounters a polarizer oriented at an angle θ that we can control. The schematic of the experiment is shown below



Question 5 Calculate the detection probabilities for the polarizer oriented an angle θ .

- **Task 7: Taking data** Take sequential data for suitable angle settings of the polarizer. Use the same program as in the previous part. Again, you must decide the range and increment.

Question 6 Make a graph of the normalized detections on each detector (i.e., $H_V/N_{V_{\max}}$ and $H_H/N_{H_{\max}}$) in the same graph along with theoretical predictions. Measurements should be symbols with error bars and theory/expectation should be a continuous line. Explain the graph and the action of the polarizer.

3.4 45-Degree Basis

We can also analyze the photons in a different basis. Here we will use the 45-degree basis.

• **Task 8: Setting the 45 Basis:** There are several steps:

- Set the polarizer to 90° .
- To set up the 45 basis we need to make sure that the detectors are detecting photons in the $|+45\rangle$ and $|-45\rangle$ states. To do this we rotate the mount on the rotating arm, which has the half-wave plate set to 22.5° . This places the waveplate before the polarizing beam splitter, as shown in Fig. 9.
- Slide the rotating half-wave plate into position. The apparatus should look like the schematic of Fig. 9.

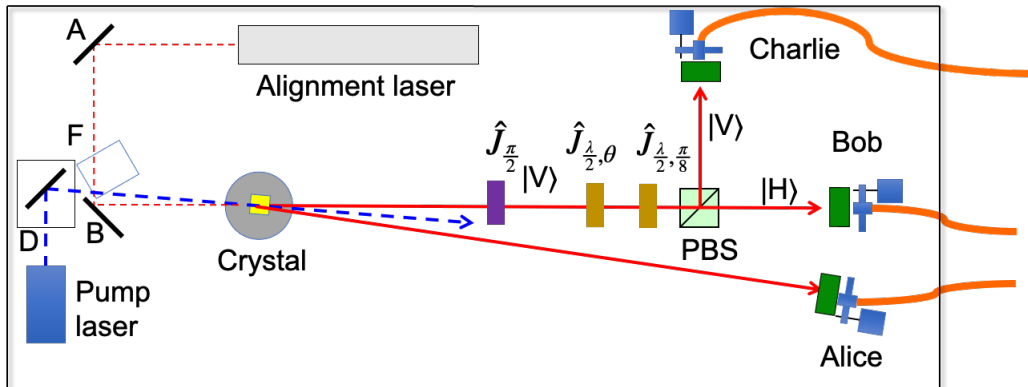
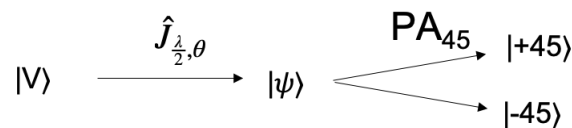


Figure 9: Setup for measuring in the 45 basis.

3.4.1 Prediction

We can understand this experiment the following way: A photon in state $|V\rangle$ goes through the half-wave plate set to angle θ . Then it goes to a polarization analyzer in the 45 basis. The schematic of the experiment is shown below



The way to understand the analyzer in the 45 basis is as follows. We put a half-wave plate set to 22.5° before the polarization beam splitter. The probability of detecting in the through direction is

$$P = |\langle H | \hat{J}_{\frac{\lambda}{2}, \frac{\pi}{8}} | \psi \rangle|^2. \quad (7)$$

It could be rewritten as

$$P = |\langle \phi | \psi \rangle|^2, \quad (8)$$

where

$$|\phi\rangle = \hat{J}_{\frac{\lambda}{2}, \frac{\pi}{8}}^\dagger |H\rangle = | +45 \rangle. \quad (9)$$

Similarly, for the reflected photon

$$\hat{J}_{\frac{\lambda}{2}, \frac{\pi}{8}}^\dagger |V\rangle = | -45 \rangle. \quad (10)$$

The significance of this is that the half-wave plate in series with the polarizing beam splitter becomes a polarization analyzer in the 45 basis.

Question 7 Calculate the detection probability of measuring the photon in states $|+45\rangle$ and $|-45\rangle$.

3.4.2 Task 9: Taking Data

Repeat a stepwise measurement, similar to previous ones to show that you are indeed measuring in the 45 basis.

Question 8 Plot the normalized recordings from the detectors Bob and Charlie (in coincidence with Alice), symbols with error bars. Add as solid lines the calculated probabilities. State your conclusions.

3.5 Shutting down

Follow the steps to finish. Do not close any of the windows.

1. Turn off the detectors. The digital display should read 0.
2. Block the laser. The purple glare should disappear.
3. Slide the wave plate out of the path of the beam.
4. Move the fixed-angle waveplate out of position, as you found it.
5. Upload your Excel file with data.