Lab 5 Delayed Choice - Remote Lab

Phys434L Quantum Mechanics Lab
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1 Theory

In 1983 John A. Wheeler, a famous theoretical physicist, proposed a thought experiment that introduced a striking aspect of quantum mechanics.[1] He called the concept *delayed choice*. In this lab we recreate a delayed-choice experiment with entangled photons. The experiment is not long, but has to be done very carefully.

1.1 The Set-up

In our previous experiments, one of the photons went through the interferometer, passed through a 40-nm filter, entered a 2-m optical fiber and reached a detector. The detector produced squared digital-electrical pulse per photon that was 3.3-V or 5-V in height and about 50-ns in duration. Each pulse traveled through a 2-m coaxial electrical cable arriving at a digital circuit that counted it and analyzed its coincident arrival with the pulse generated by the twin photon.

Because of the filter, the photons are in a superposition of energy states. Since we cannot know the exact energy of a photon going through the filter, the photons are in a superposition of energy states. They form a *wavepacket*. Earlier in the semester we discussed the concept of the coherence length, which we used to align the interferometers, and which we defined as the length of the photon wavepacket. If the bandwidth of the photon is $\Delta\lambda$, the coherence length is

$$\ell_c = \frac{\lambda^2}{\Delta\lambda}. \tag{1}$$

In our case, since $\lambda \simeq 810$ nm and $\Delta\lambda = 40$ nm, then $\ell_c = 16$ μm.

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[1] J.A. Wheeler, "Law Without Law," in *Quantum Theory and Measurement*, J.A. Wheeler and W.H. Zurek Eds. (Princeton University Press, 1983
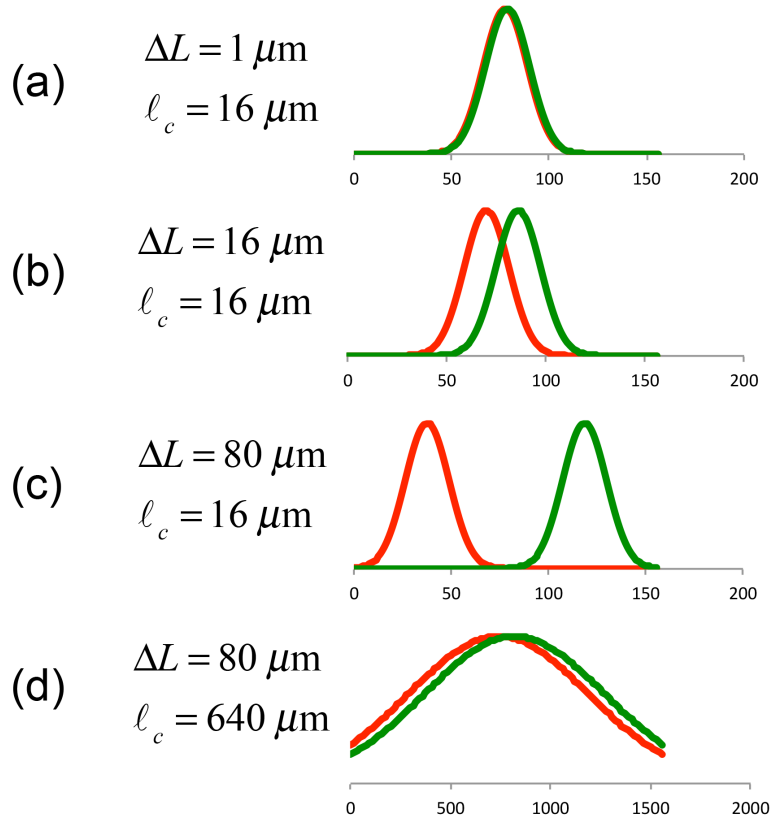
(a) $\Delta L = 1\,\mu\mathrm{m}$
$\ell_c = 16\,\mu\mathrm{m}$

(b) $\Delta L = 16\,\mu\mathrm{m}$
$\ell_c = 16\,\mu\mathrm{m}$

(c) $\Delta L = 80\,\mu\mathrm{m}$
$\ell_c = 16\,\mu\mathrm{m}$

(d) $\Delta L = 80\,\mu\mathrm{m}$
$\ell_c = 640\,\mu\mathrm{m}$

Figure 1: Comparison of Gaussian wavepackets of coherence length ℓ_c for the different path length difference ΔL in the interferometer.

1.2 The Plot

If the amplitude wavepackets for the light going through both paths overlap, then there is interference. The condition for this is

$$\Delta L < \ell_c. \tag{2}$$

If we see interference, we can say that we are observing the wave nature of light. The paths are indistinguishable and quantum mechanics argue that there is a superposition of amplitudes for the light going through the two possible paths. Figure 1(a) depicts the wavepackets with Gaussians.

Suppose now that we increase ΔL to be comparable or slightly larger than ℓ_c. In that case we will have partial knowledge of the path information. The wavepackets will not overlap exactly, so the interference will not be perfect. The wave functions for the two arms cannot interfere completely. Thus, fringes will not show complete destructive or

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constructive interference. We quantify this via the visibility of the fringes, defined as

$$V = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}}, \tag{3}$$

where $N_{\max}$ and $N_{\min}$ are the maximum or minimum counts. When there is complete interference, $N_{\min} = 0$, and so $V = 1$. When there is no interference $N_{\max} = N_{\min}$, and so $V = 0$. Anything in between characterizes the partial knowledge of the path information. This situation is depicted in Fig. 1(b). As we increase the ΔL further, we see a decrease in the visibility of the fringes due to a decrease in overlap of the two copies of the amplitude wavepacket.

When $\Delta L \sim 80 \ \mu\text{m} \gg \ell_c$ there is no temporal overlap between the wavepackets coming from the two arms of the interferometer (Fig. 1(c)). Thus, there is no interference, and $V \to 0$. We can think of this in an alternative way: the paths are distinguishable because we can do a timing measurement and find that traveling the shorter path results in an electronic detection at a distinguishably earlier time than when traveling the long path. This can be interpreted as the particle view: the knowledge of the path identifies the photons behaving as particles taking an individual path.

1.3   The Twist

The length of the wavepacket is determined by the bandwidth of the filter. What if we change the bandwidth of the filter to 1 nm? The length of the wavepacket will increase 40 times to 640 μm, so $\Delta L < \ell_c$. Notice the overlap of the wavepackets shown in Fig 1(d). Will there be interference? Yes.

The photons going through the interferometer are correlated in energy with their twin photons (remember that their energies have to add to the energy of the pump photon). The partner also has a filter. If we change the bandwidth of one filter, effectively means applying it to both, since we record the coincidences, or when both photons go through their respective filters. What then if instead of changing the filter on the photon that goes through the interferometer, we change the filter of the photon that does *not* go through the interferometer? It should not matter!

Moreover, there is no stipulation on when the photon should pass through the filter. Quantum mechanics does not care, which was the point of John Wheeler. So in this lab we will put this to the test. We will have the photon not going through the interferometer go through the 1-nm filter *well after* the other photon-the one going though the interferometer-has been detected. We will do this by sending the photon that does not go through the interferometer into a 20-m optical fiber. Because we detect the electronic signals of the two in coincidence we will add a corresponding length of electrical cable on the signal of the photon that goes through the interferometer. The schematic of the apparatus is shown in Fig. 2.

Should we see interference? The answer is a resounding yes! It seems like an illogical back action into the past: specifying the coherence length of the photon going through the
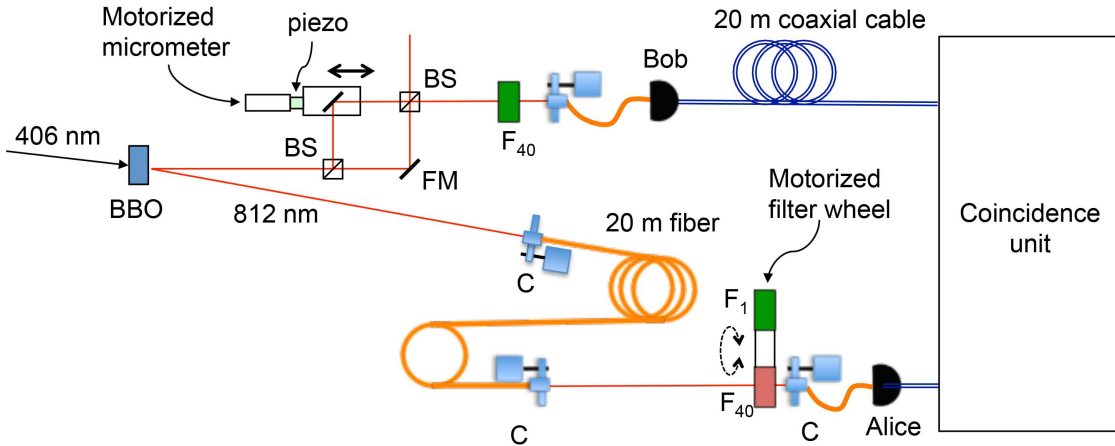
Figure 2: Apparatus for the Delayed-Choice Experiment. The photon heading to Alice gets is sent through a 20-m fiber. After the fiber it gets sent into free space where it passes through a filter to enter again into a collimator that sends the photon to a detector. By the time Alice's photon passes through the filter, Bob's photon is detected. To compensate the time imbalance, the electronic pulse from Bob goes through an extra cable so that both pulses arrive to the coincidence unit at the same time.

interferometer after it is dead. Are we sending the terminator to kill Sarah Connor and make John Connor disappear?

1.4 The Resolution

How can we change the pattern that we see after the photon has been detected? The wave or particle aspect seems to be determined after the deed is done. John Wheeler also said "a measured phenomenon is not a phenomenon until it is measured." For quantum mechanics there is no back action into the past. The above analysis had a flaw. It did not consider the two photons for what they are: entangled in energy. Their wavefunction is a *two-photon* wavefunction:

$$|\psi\rangle = \int A(E)|E\rangle_1 |E_0 - E\rangle_2 dE, \tag{4}$$

where $A(E)$ is the amplitude of producing a given pair of energies $(E, E_0 - E)$, and where E_0 is the energy of the pump beam.

In the following, we show an analysis of how quantum mechanics explains the experiment. The interferometer can be represented by the operator $\hat{U}$ acting on photon 1. If the coefficients of reflection and transmission of the beam splitters are r and t, and if the path-length difference of the arms of the interferometer is x, then the after the interferometer the state of the photons is

$$|\psi'\rangle = \hat{U}|\psi\rangle \rightarrow \int A(E)(1 + e^{i2\pi Ex/hc})|E\rangle_1 |E_0 - E\rangle_2 dE \tag{5}$$

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We then pass the photons through two filters with transmission functions $a_1(E)$ and $a_2(E)$. Detectors following the filters complete an energy-projective measurement into states

$$|\psi\rangle_i = \int a_i(E')|E'\rangle_i dE' \tag{6}$$

$i = 1, 2$. The detection probability is then given by

$$P = \left|\langle\psi|_1 \langle\psi|_2 |\psi'\rangle\right|^2. \tag{7}$$

Replacing the expressions for the states that are detected gives

$$P = \int a(E) \left|rt(1 + e^{i2\pi Ex/(hc)})\right|^2 dE, \tag{8}$$

where $a(E) = A(E)a_1(E)a_2(E_0 - E)$. That is it. The probability incorporates the product of the filter curves, so the final probability is determined by the narrowest filter, regardless of which one it is.

As an example consider that the filter has a "flat top," being constant $a(E) = 1$ when $E_1 \leq E \leq E_2$, and 0 otherwise; then the integral is straightforward to solve. Skipping the details, Eq. 8 simplifies to

$$P = \frac{1}{2}\left(1 + \frac{\sin\alpha}{\alpha} \sin\frac{2\pi x}{\overline{\lambda}}\right), \tag{9}$$

where $\alpha = \pi \Delta E x/(hc)$, with $\Delta E = E_2 - E_1$ and $\overline{E} = (E_1 + E_2)/2$. Note also that

$$\alpha = \frac{\pi x}{\ell_c} \tag{10}$$

When $x \ll \ell_c$ ($\Delta L \ll \ell_c$) we have that as $\alpha \to 0$, then $\sin\alpha/\alpha \to 1$, so the probability is

$$P = \frac{1}{2}\left[1 + \sin\left(\frac{2\pi x}{\overline{\lambda}}\right)\right], \tag{11}$$

with $\overline{\lambda} = hc/\overline{E}$, which corresponds to interference that varies with the path length difference x. As x increases to the limit when $x \gg \ell_c$ ($\Delta L \gg \ell_c$) , or $\alpha \to \infty$, then $\sin\alpha/\alpha \to 0$, the interference disappears and the probability becomes

$$P = \frac{1}{2}. \tag{12}$$

Getting an expression for the intermediate range is complicated, so we will skip it. What will happen is that as ΔL increases beyond ℓ_c the interference switches smoothly from Eq. 11 to Eq. 12. This manifests in the visibility going from 1 to 0.

The bottom line is given by Eq. 7. Each detector collapses the state via a measurement. There is no restriction on either the time when the two projections are made nor their order. The best answer that quantum mechanics tells us is that when the first detection is made, the data contains both wave an particle information. This experiment is a second recreation

of the quantum eraser, but in this case we use time-energy projections to make the paths distinguishable or not. When we perform the second detection we select which subset of the data we choose to observe: wave or particle. Makes sense? In the words of Bohr: "If you are not disturbed by quantum mechanics, you do not understand it." For more information we published an article about this.[2]

2   Parts

Qty	Part	Description/Comments
1	20-m fiber	Multimode.
1	20-m of coaxial cable	
1	Collimator mount	Mounted on a mirror mount
1	Collimator mount	From detector C in previous experiments
1	40-nm filter	mounted on rotating blade
1	1-nm filter	mounted on rotating blade
1	motorized micrometer	to provide 5-μm increments in path length
1	motorized rotation mount	mounting filters in a blade to switch them

3   The Remote Apparatus

3.1   General

You log into the lab computer using remote desktop. It is a PC machine different from previous lab:

$$\text{Ho313-96139W.colgate.edu}$$

Then you log into the PC:
Username: phas2
Password: Fr2=Gm1m2
Once you do this, your screen will appear as something like what you see in Fig. 3. You will see 4 windows. One is a view of the apparatus from a webcam (upper left in the photo). The window on the lower left is a serial interface to an Arduino based circuit that has 3 functions: To turn ON/OFF the power to the (blue) pump laser, detectors (more on this below), and illuminating LED.

In the window with the Matlab platform there are 2 programs we will use: one rotates a filter holder to switch from one filter (40 nm) to the other (1 nm). The second program does a piezo scan to record the photon data.

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[2] "A time-energy delayed-choice interference experiment for the undergraduate laboratory, Jhonny Castrilln, Enrique J. Galvez, Boris A. Rodriguez, and Omar Caldern-Losada, *European Journal of Physics*, **40**, 055401 (2019).
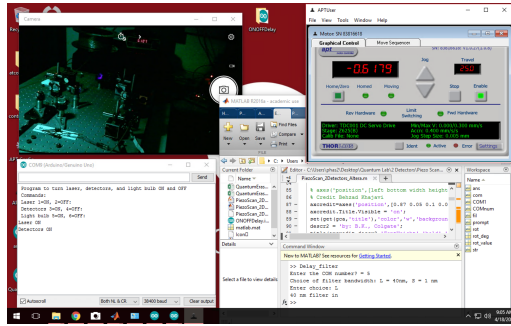
Figure 3: Screen of the Desktop that controls the experiment in the lab. The computer name is: "Ho313-96139W.colgate.edu". It has a webcam window (upper-left), a serial interface window (lower left) and a Matlab window (lower right), and the micrometer control (upper right).

3.2   Webcam

The webcam allows you to see the parts of the apparatus, as seen in Fig. 4. Note that there is visual evidence that the laser is ON (by the glare in the beam dump) and that detectors are ON by the voltage applied to them. There is also a white LED (not seen) that illuminates the setup a bit better so you can see the various parts. **Note: detectors must be OFF when this LED is ON.** These parts are seen in Fig. 4.

3.3   Commands

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

3.3.1   Laser and detectors ON/OFF

The laser must be turned ON at the very beginning. Be mindful that there is a warm-up time of several minutes for laser to reach a stable output. The power to the laser and detectors is controlled by a program that runs on an Arduino-based circuit (through the COM9 serial port). The 2 detectors (Alice and Bob) can be turned ON or OFF at any time. You should turn them OFF when not in use.

   The Arduino program is always running. A serial window is shown in Fig. 5. 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 follows:

- **Laser ON**: On the command line type "1" . Turn it on before you start the experiments. You can do two a visual verification via the webcam that this action has taken place: you can see a purple glare coming out of the beam dump.

- **Laser OFF**: On the command line type "2" . Turn it off once you are done with the lab session.
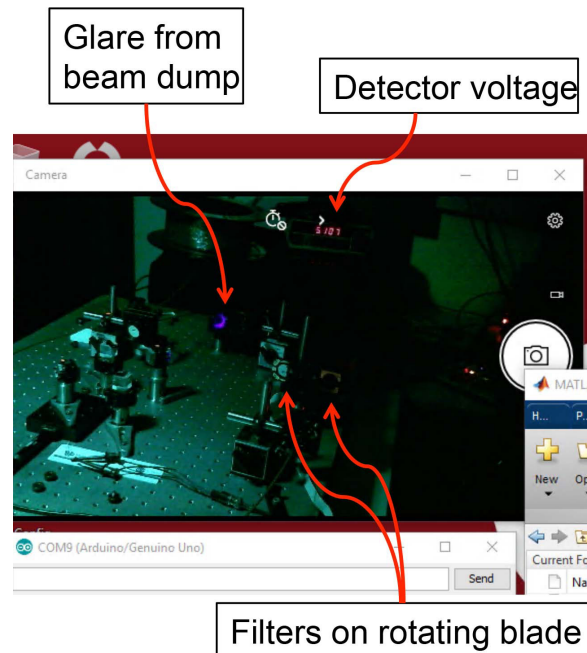
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Figure 4: Image from the webcam that allows the user to see the apparatus.

- **Detectors ON**: On the command line type "3" . Turn it on before you start the experiments. There is 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.

- **LED ON**: On the command line type "5" **Detectors must be OFF when this LED is ON**. Use it only to inspect the apparatus.

- **LED OFF**: 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.

3.3.2 Micrometer Control

On the upper right of the desktop is a window of the program that controls the motorized micrometer that makes coarse translations of the mirror (and hence change ΔL). A close-up
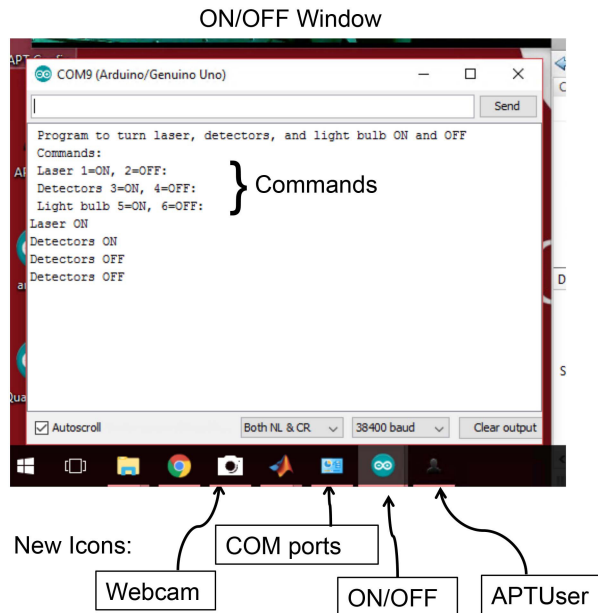
Figure 5: Screen of the desktop window connected to an Arduino-based circuit that exerts ON/OFF controls for the experiment in the lab. It is used to turn the lasers, detectors and illuminating LED on/off. Also shown in the figure are the icons for the different programs.

is shown in Fig. 6. There is a display that reads the micrometer position in mm.

Indicators/Controls:

- **Position Display** This is a digital indicator that prominently displays the position of the micrometer in millimeters, as shown in the figure. The position shown, -0.6179 (mm), is the zero-path-length position.

- **Changing Micrometer Position** To change the position of the micrometer click on one of the two triangular buttons under the "jog" label. Each click advances forward or backward, depending on the button. The position of the stage, and consequently the path length, changes by 5 μm. You can see the micrometer motion by the change in the value of the position.

- **Troubleshooting** Sometimes the control loses the connection and gives an error when you click the "jog" button to change the position. When this happens we need to close the APTUser window and click on the "APTConfig" icon on the desktop. This opens a window that has 3 tabs. Under "Simulation Configuration" click on the button "Load," which brings a pull down menu. Select "Lstage," which loads the driver on a screen. Now click on the "Stage" tab and you should see some specification in a window. If so, you are all set. Close APTConfig. click on APTUser icon on the desktop and click on "Settings" and change the step distance to "0.005" (we must do this because the program defaults to 0.1 mm step size).

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APTUser Window (to operate motorized micrometer)

Current position of micrometer in mm

Forward

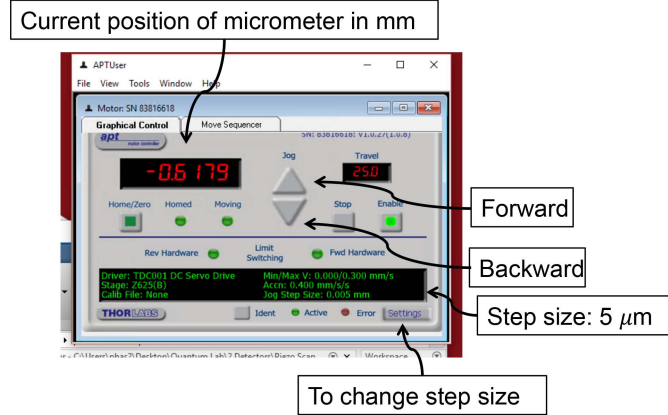Backward

Step size: 5 μm

To change step size

Figure 6: Screen of the desktop window connected to an interface that controls the micrometer that moves the translation stage. This effectively changes the path length ΔL by coarse amounts. The increment is set to 5 μm.

3.3.3 Filter-Mounted-Blade (Matlab)

In the Matlab command window (lower right part of Fig. 3) enter "Delayed_Filter", as shown in the close-up of Fig. 7 .

When the program runs, all actions are entered in the same command line. The commands are:

- **COM Port:** You get prompted for this. Enter "5" .

- **Filter**: You get prompted to enter the filter:

    - "L" for the long-bandwidth filter (40 nm),
    - "S" for the short-bandwidth filter (1 nm).

3.4 Piezo Scan

This is the standard Matlab program to do scans. Go to the directory:

"Desktop-QuantumLab-2Detectors-Piezo Scan", and run "PiezoScan_2Detectors_Altera".

Effectively this program does a fine scan of the interferometer path length. It is controlled by another Arduino circuit that scans the voltage that is applied to the piezo-eletric to change the path length by small amounts (of the order of tens of nm). The GUI screen for this program will appear with several entries:

- **COM Port of Counter**: Enter "6" so it reads "COM6"

- **COM Port of Arduino**: Enter "8" so it reads "COM8"
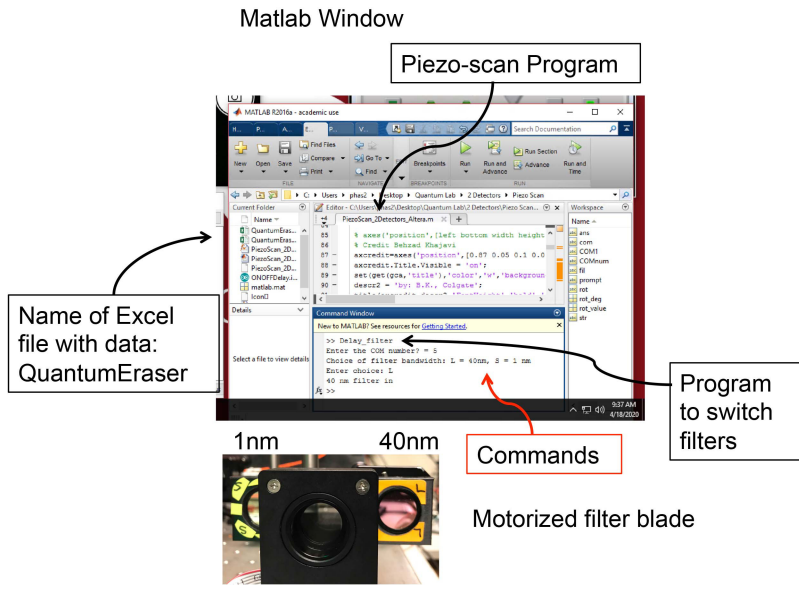
- **Start Voltage "Vi"**: Enter "1"

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Figure 7: Screen of the desktop window for the Matlab programs (2). One controls the Piezo scan and the other flips the filters through the command line. Also shown is a closeup of the motorized filter blade.

- **End Voltage "Vf"**: We recommend "5". The maximum value is 9.

- **V Increment "dV"**: Use "0.05"

- **RUN** Click "RUN" button to start the scan. **Very Important**: If you made a mistake do not abort the scan. Matlab gets very confused and may give an error whe you try to run again. If that happens, close Matlab and reopen it.

- **Excel File Name**: The data will be placed in a spreadsheet named "QuantumEraser".

4 Procedure

The lab has several moving parts that are controlled remotely. Here is a big picture of the experiment. At the start $\Delta L \sim 0$. So when you take a scan, you will see nice fringes. You do this with the long-bandwidth filter. Then you will increase ΔL and take a scan, and the visibility will go down. Continue increasing and scanning until the visibility is zero. At that point we will switch filters and take one last scan with the short-bandwidth filter.

4.1 Cold Start

1. **Laser ON**: Turn Laser ON (enter "1" in the serial window; see also the commands above). You should see the purple glare on the beam dump when the laser is ON.
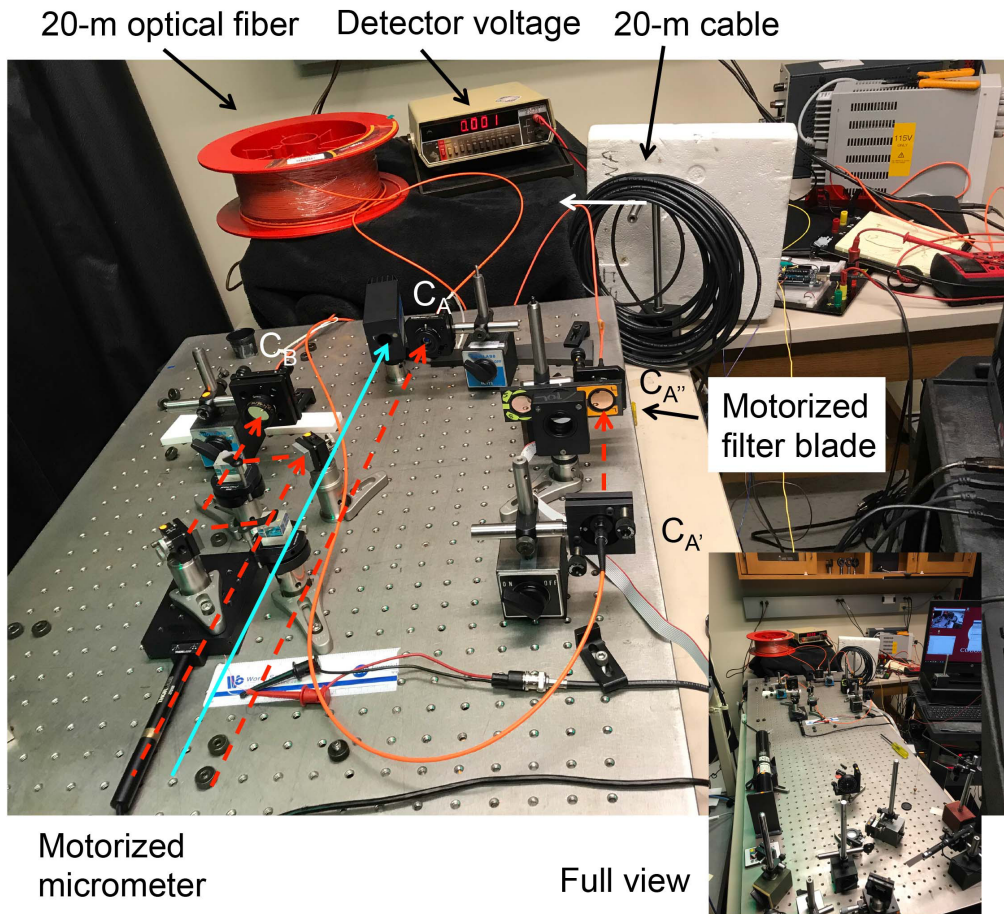
Figure 8: Photo of the lab setup. Dashed (red) lines show the path of the down-converted photons. Fiber collimators are labeled. The photon going to Bob's detector goes in through C_B. The other photon goes into the 20-m fiber through C_A, comes back out into free space through $C_{A'}$, goes through the filter on the filter blade and enters another fiber through collimator $C_{A''}$ to finally reach Alice's detector.

2. **Inspection** At this point the digital display of the detector voltage should read "0.000".

   - Turn the LED on via entering "5" in the serial window. This should illuminate the setup.
   - Identify all the key parts of the lab (interferometer, 20-m optical fiber reel, 20-m coaxial cable filter blade).
   - Also follow the path that the photons that go to Alice take through space and fibers. Use the diagram of Fig. 2 and Fig. 8 as reference.

3. **Checking the Filter-Blade Rotation**: At this point check that the moving parts work.

   - The filter should be set to the long bandwidth. Switch it to the short bandwidth by running the "Delay_Filter" program in the Matlab command window.
   - Enter "5" for COM port,
   - Enter "S" for the short-bandwidth filter. You should see the filters switch. Yeah, that was fun! (for the professor...)
   - Switch to the long-bandwidth filter by running the program again and entering "L" to switch the filters.

4. **Checking the micrometer**: Click the upper-triangle "jog" button in the APTUser window. You should see the digital readout, measuring the position, advance by 0.005 (i.e. 5 micrometers). If this happens then all is working. Click the lower triangle to return to the original setting.

5. **Turn LED OFF**: Now we are almost ready to start. Turn OFF the LED (i.e., type "6" in the ON/OFF serial screen).

6. **Turn Detectors ON**: In the serial window enter "3." The digital readout should settle around 5 V. We are ready to start taking data!

4.2   Taking Data

7. Before you start, get organized. We will take about 11 scans. Do not worry, each takes about 80 s. The apparatus records the scans in the "QuantumEraser" Excel file in tabs labeled by the time they were taken. So the "Recorder" (a group member) must record for each scan the following information: time, micrometer position, approximate maximum (N_{max}) and minimum (N_{min}) coincidence counts and the accidental-count reading corresponding to the maximum ($N_{acc-max}$) and minimum ($N_{acc-min}$) counts.

(Another group member can read out this values off the screen as that data is being taken). Also this person must get a quick value for the visibility:

$$V = \frac{(N_{max} - N_{acc-max}) - (N_{min} - N_{acc-min})}{(N_{max} - N_{acc-max}) + (N_{min} - N_{acc-min})} \tag{13}$$

(It is good practice to keep track of the data as the experiment goes on.

8. With 40-nm filters for both photons take a scan with the program

   "PiezoScan_2Detectors_Altera" entering a "5" for the end voltage (Vf), and set counter to (COM6) and Arduino to (COM8) ports. Hit "RUN" and you should see nice fringes in the singles and coincidences.

9. From now on you can depart from the instructions below on how you repeat the scans. Since you are an experimenter, should make some executive decisions. Just to give heads up: early-on the data changes quickly, but as ΔL increases the changes will be less pronounced, so you can take larger steps. Below we have some suggested method. Click the upper-triangle jog button in APTUser to advance the micrometer by 5 μm. Take a scan. Find V for the data. It should be lower than the previous value; we are getting the photons out of their comfort-wave zone.

10. Repeat the procedure above (jog click, scan) until you have advanced about 25 μ (you can decide for a different amount). At this point you will see that the visibility is not changing by a lot, so you can now take larger steps, (for example several jog clicks at a time).

11. Repeat the scans with the larger increments until you reach about 125 μm of total displacement from the start. The fringes must now have a visibility that is hard to determine, close to zero.

12. Here is a momentous point: Turn the detectors OFF, switch the filter to the short-bandwidth one, turn the detectors back ON, and take a scan.

13. The data will be noisy but strikingly different. Notice that the singles counts for Alice are way down. That is the effect of reducing the bandwidth of the filter by a factor of 40. For your report you can take more scans with the same conditions and add them later.

14. At this point you can take any more data that you want, so you understand the consistency of the data. If you switch the filters again, make sure the detectors are off while you do that.

4.3   Shutdwon

15. Return the micrometer to the original position (via jog clicks). Be patient: one click at a time.

16. Turn detectors OFF.

17. Switch the filter to the long-bandwidth one.

18. Turn the laser OFF.

19. Run again the piezo program with final voltage Vf set to 2. This is to leave he piezo with a low voltage applied to it. This is not for taking data, so the laser and detectors do not need to be on. Once that scan is done, you rare done with the lab.

20. Save your data.

4.4   Analysis

21. Explain the experiment, and your procedure.

22. As a form of report, plot the data sets and one final plot of V vs. ΔL.

23. Explain your findings, referring to the figures with data.

24. Make concluding remarks about the significance of the experiment.