

Remote Quantum Optics Labs

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ABSTRACT

When situations make it difficult for students to be physically present in the laboratory, there is a need to provide remote instructional offerings. This is a particularly acute problem in upper-level physics laboratories because they involve the use of sophisticated equipment for the investigation of advanced topics. The possibility of automating such experiences presents itself as a possible solution. In this article I present the offering of an automated quantum optics lab for advanced physics students. I do so by automating the laboratory components via actuators and sensors controlled through serial connections. Live images of the laboratory provide visual inspection of the apparatus and sensors. All of these components are connected to a personal computer that students can control by remote access. The experience provides a new paradigm for experimentation, giving students experience on laboratory work with a remote apparatus at flexible times, making the experiment a form of homework assignment.

1. INTRODUCTION

Prompted by the covid-19 health crisis of 2020, educators have been forced to do their instruction by remote means. This has put significant stress on laboratory-based instruction. In the case of physics, there are distinct types of labs at the introductory and advanced level. Some of the values of the advanced lab are the significance of the experiment, experience with sophisticated equipment and in-depth level of data analysis and reporting. These laboratories also involve hands-on activities, such as alignment, calibration and experience connecting various pieces of equipment for powering and data acquisition.¹ The inability to do in-person labs left many of these experiences unavailable. In an effort to continue to provide some form of advanced laboratory experience for our students we devised a way to automate the experiments and set up the hardware so that students could do the labs remotely. The experiments involve sophisticated hardware, so the absence of hands-on experience is missed, but the remote experiences may compensate by providing other opportunities that were not anticipated: higher flexibility, experience with remote troubleshooting or problem-solving, and the possibility that some laboratory exercises be attached to a course without a dedicated laboratory section.

The laboratories that we focus on are correlated-photon experiments that underscore the fundamentals of quantum mechanics.² They are part of an educational trend to emphasize the fundamentals in the teaching of quantum mechanics, which has benefitted by the publication of new textbooks on the subject.²⁻⁴ They also underscore the emergence of quantum information, a new field or research and technology that uses quantum systems to encode and process information.⁶ At our institution we developed a set of laboratories to illustrate these concepts,⁷⁻¹⁰ which currently form part of an add-on laboratory component for a course on quantum mechanics. One component of the in-person laboratories involves optical alignments. As described in this article, we have converted the labs for remote operation. We had to forgo in-person activities due to the closure of the university for health reasons. However, we were able to incorporate other aspects of the lab in the remote experience, such as decisions on how to acquire the data, performing actuator-driven optical-beam manipulations and calibrations, data acquisition and data recording. In a period of several weeks we offered 3 experiments: the quantum eraser,^{7,8} delayed choice single-photon interference,⁹ and quantum entanglement.¹¹ In a more recent version of the lab we continued the remote offerings adding a new lab on polarization-state projections.⁷

In the remote instructional offering, at an agreed time, students connected to each other by an online resource, such as Zoom. A designated student accessed the lab computer by remote desktop, and shared his or her screen

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with the other group members. During the experience students decided on the data that they need to take, acquired it, downloaded it, and did the corresponding analysis and reporting off-line. The instructor, available online, provided help and feedback.

2. THE REMOTE APPARATUS

An overall picture of the apparatus for doing remote experiment with entangled photons is shown in Fig. 1. It shows the optical apparatus set up on an optical breadboard. The experimental parameters were automated so that a personal computer controlled them. This enabled the remote control of the experiment. The lab was located in a basement of the college building, so vibrations were not a factor. The setup was curtained off and the lab had a laser warning sign above the door, so only authorized personnel could enter. The apparatus was pre-aligned and tested by the instructor. Below we specify the parts that were needed to set up the remote operation.

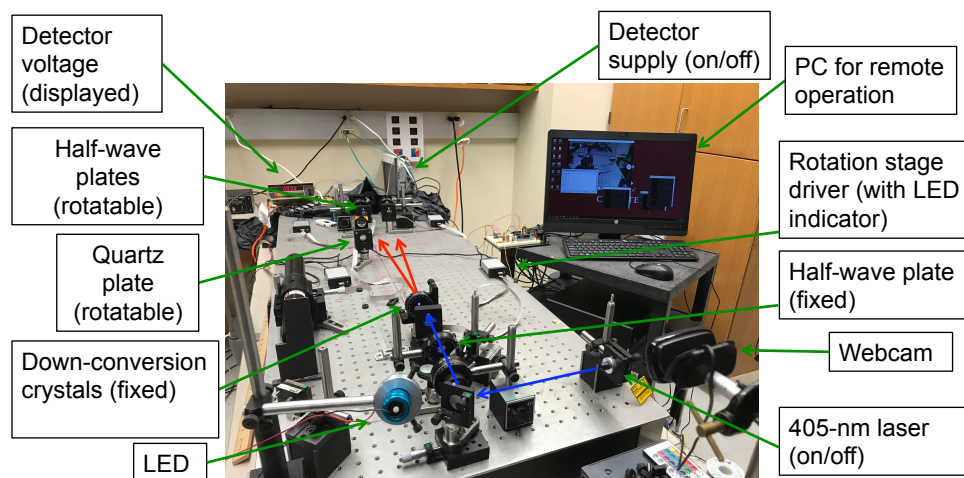


Figure 1. Photo of the apparatus for one of the experiments, displaying optical components, actuators, sensors, and the dedicated personal computer (PC) used for the control of the experiment. Trajectories of the source laser beam and down-converted photons are seen in blue and red, respectively. The actuators controlled the power of the pump laser and detectors, and motorized rotation stages. A webcam provided visual sensing of the voltage applied to the detectors, displayed on a digital voltmeter, and a view of the motion of the rotation stages.

2.1 Hardware Components

Remote labs require the components listed in Table 1. A personal computer (PC) that is reasonably recent is needed so it does not run too slow with the remote desktop program. A green LED that is not too bright is needed so that the webcam can give a view of the apparatus while data is taken. These LED's have a bandwidth that is narrow enough to not interfere with the detection of down-converted photons.

A webcam is a vital ingredient. At least one webcam is needed. It provides a view of the apparatus and its vital components during the experiment, as shown in Fig. 2. Mechanical or electrical parts can fail or may not be set up correctly, so visual inspection helps in determining why the data is not showing the expected results. Instructionally it is useful because it lets students correlate a schematic diagram in the instructions with the real device in the remote location. It gives reassurance that what appears in the remote computer reflects a live experiment. This can be important for the remote instructor as well. The apparatus can also be set up to train students in troubleshooting, such as overcoming some challenge, or calibrating an optical component using the data.

The start and end of the laboratory experiment turning the apparatus on and off. In this case it involves the laser and the detectors. A simple arrangement involves using an Arduino-UNO board to drive relays that control the power applied to the laser and detectors. The laser may not be stable immediately after being turned

Table 1. Example of the hardware requirements for a remote quantum-optics lab.

Qty	Part	Description/Comments
1	Desktop PC	Should be a 1-2 year old machine with Windows 10 preferably
1	Webcam	Installed on a stand, overlooking the apparatus. USB connected to the Desktop
1	Green LED lamp	Of the kind that can be bought at hardware stores; not too bright.
1	Arduino UNO board	This is for control of pump laser, detectors, and optionally other components. Other Arduino boards work as well.
1	Electric breadboard	The kind used in intro electronics labs.
3	12-V relay	Minimum current for contacts is 2 A.
2	Motorized rotational mounts	USB controlled- We use Pacific Laser RSC-103E.
1	12-V power supply	Standard, 0.5 A for powering the relays.
1	Laser-beam shutter	Optional. Simple electrical on/off optical shutter for blocking the laser beam.

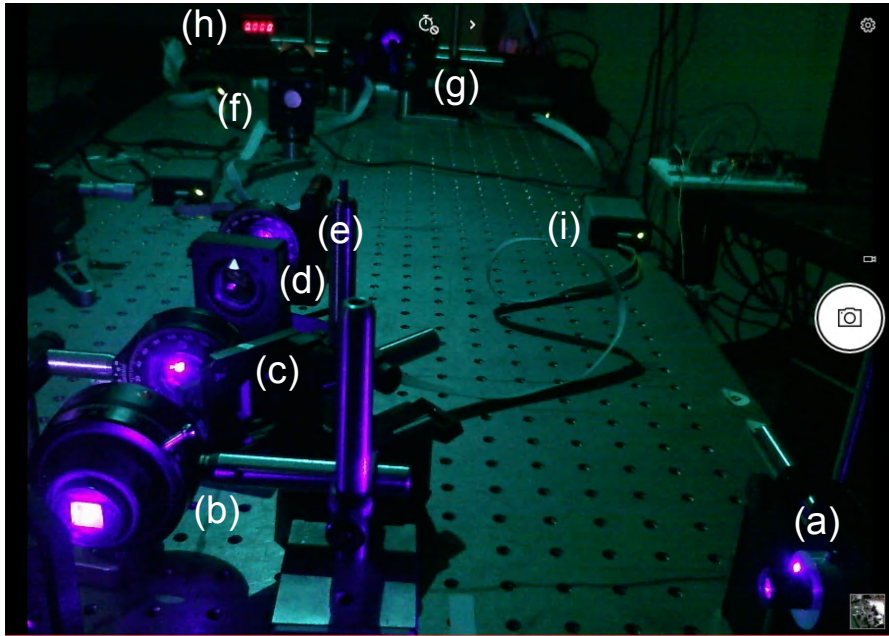


Figure 2. The webcam provides a continuous view of the apparatus and its controls and indicators. One can see the laser (a), the optical elements involved in the preparation of the state (a-f), and detection components (g). Sensors include the digital readout of the voltage applied to the detectors (h) and rotation-drivers (i).

on, so this action must be done at least 15 minutes before taking data. If it takes longer for the laser to achieve stability, the laser can be turned-on well before the experiment, and for safety, block the output beam with an electromechanical shutter. In this case the relay would activate the shutter to unblock the beam. The laser is likely to have a power above 20 mW, which makes it a class IIIb laser, demanding safety precautions in the lab where the equipment is located.

Verification of these power switching actions is important. Seeing optical elements scatter pump-laser light with the webcam reveals that the pump laser is on, as seen in Fig. 2. To verify the voltage applied to the detectors we could view the output of a digital voltmeter, as shown in Fig. 2. Alternatively one can read the input of the detector voltage with an analog input of the Arduino board. Since the Arduino boards have plenty I/O outputs, additional outputs can be used for signaling and safety interlocks to the lab.

Other hardware components can include rotation and linear stages that are motorized. These can provide repeatable motions that make the experiments more reliable than in a hands-on situation. In setups involving piezo-electric elements, suitable drivers and electronics may be used, controlled via the Arduino board.

2.2 Software Components

A list of the software needed is shown in Table 2.

2.2.1 Lab PC End

The first step in the remote control is to set up the lab PC for remote desktop. The following steps are needed (warning: these commands can quickly become obsolete):

1. Get computer name at:

<https://support.office.com/en-us/article/do-you-need-help-locating-your-computer-name-00384381-8aa9-4398-b81b-475f09fed618>

Ensure user is in the Group, “Remote Desktop Users”. Use option 1 or 2 in the following link to access the Computer Management app:

<https://www.sevenforums.com/tutorials/7539-local-users-groups-manager-open.html>

- (a) Under “Local Users and Groups” select “Groups.” Then open “Remote Desktop Users.”
 - (b) Add “Domain Users” so that anyone at the school network can log on. Or just enter the username of the desktop. Select “Check Names;” you may have to give your domain login information so that the name can be checked with the domain registry.
2. Set the power plan to “High Performance” so that the computer never goes to sleep:
<https://www.makeuseof.com/tag/windows-7-power-options-sleep-modes-explained/>
 3. Install the software that is needed for driving the electromechanical components:
 - (a) Install Matlab, Labview or Python, which ever program is needed for data acquisition.
 - (b) Install the Arduino software. It can be downloaded from <https://www.arduino.cc/>
 - (c) Install a serial port reader. We found PuTTY to be a convenient platform, but any software that provides such a function is suitable. One can download PuTTY from <https://www.putty.org/>
 - (d) Install the driver software for the webcam.

Table 2. Software requirements for remote labs.

Part	Description/Comments
Webcam driver	Whatever software comes with the webcam. Convenient options are screen shots and zoom.
Arduino	Free download for controlling Arduino UNO board
PuTTY	Free download of serial port control of USB devices
Microsoft Remote Desktop	Free windows download
VPN Connection	Often required by the remote desktop program and in connection with the campus network.
Additional drivers	As necessary depending on additional remote devices used.

2.2.2 User End

The student or staff user of the remote computer must also download software into his/her machine. The steps for this are listed below. The final set of instructions need to involve coordination with the local person(s) managing local computer and network systems so that the proper username and passwords are used.

1. Set up a VPN connection to the campus network.
2. Download the Microsoft Remote Desktop client:
 - (a) Windows 10 or 7 - It may already be installed otherwise download here:
<https://docs.microsoft.com/en-us/windows-server/remote/remote-desktop-services/clients/windowsdesktop#install-the-client>
 - (b) Mac - Download from MacApp store:
<https://apps.apple.com/app/microsoft-remote-desktop/id1295203466?mt=12>
3. Open the program. Enter the name of computer to connect to and enter the username and password.

2.3 Controls

Once all is set up, the remote user logs into the lab computer using remote desktop. The screen will be that of the remote PC. We show an example in Fig. 3. You see 6 windows. One is a view of the apparatus from a webcam (upper left in the photo). The window on the lower left is the serial interface to the Arduino based circuit mentioned above that has 2 functions: To control the power to the pump laser and detectors. On the upper right is a window of the data acquisition program, which in our case uses a Matlab platform. On the bottom we see 3 screens in a front plane. They are PuTTY serial-port windows, which control the motorized rotation stages.

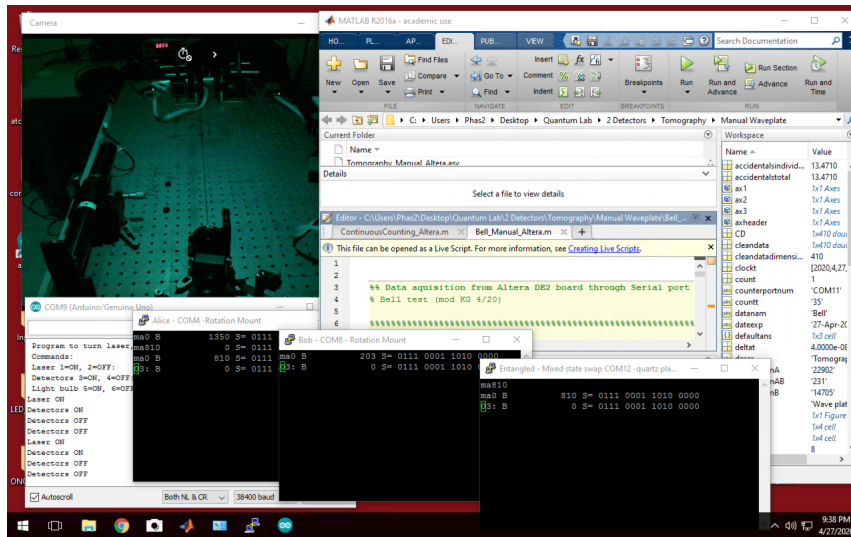


Figure 3. Screen shot of the desktop used during one of the quantum entanglement experiment. In the upper left of the desktop is the webcam view. In the lower left is the Arduino window used to control power to laser and detectors. The upper right window shows the Matlab data acquisition window and below are 3 PuTTY serial port windows that control motorized stages.

2.3.1 Laser and detectors ON/OFF

For safety reasons, the laser beam should be going through the apparatus only during the experiment. It can be enabled (disabled) by either turning it on (off), or unblocking (blocking) it if it was always on. The single-photon detectors are very light-sensitive and so it is prudent to have them on only for the duration of the experiment. In Appendix A we present various aspects of our method to implement this function using an Arduino-UNO board.

2.3.2 Rotational Controls

The experiment of Fig. 3 has controls for 3 rotational mounts. To move the particular motorized stage (Pacific Laser Inc., model RSC-103) one enters “ma” followed by the angle in ninth of degrees. It is useful to set up the serial port for full duplex, so that the user sees the command that was typed. This is also useful to keep track of the previous instructions.

Two of the rotation stages control waveplates that are placed in front of polarizers. They effectively act as rotatable polarizers for polarization projections on each of the photons. Fig. 4(a) shows the two stages. Small triangular marks indicate the orientation of the fast axis of the waveplates. When the waveplates receive the instruction to change position, one can see these components move in the webcam view.

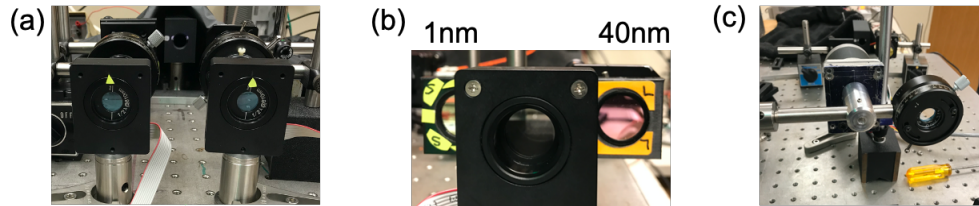


Figure 4. Photo of the motorized rotational mounts: (a) half-wave plates for polarization projections, (b) a filter blade to set the bandwidth of the filter from two possibilities, (c) a mount with a waveplate mounted on an arm rotated directly by a stepper motor to place in/out of the path of the photons.

In a different lab (delayed choice), a projection of the energy bandwidth through two distinct band-pass filters was enabled by switching between two filters. They were mounted on a blade that was rotated by a rotational mount, as shown in Fig. 4(b). In the quantum eraser experiment, we rotated a polarizer in and out of the path of the photons using a similar device, and in the quantum entanglement experiment we did the same with a thick quartz plate to change the coherence of the state of the two photons. Another way to move an optical element in/out of the photon path is by rotating an arm where the optical element is mounted via by a standard stepper motor, as shown in Fig. 4(c). The stepper motor has 200 steps per revolution and was easily controlled by an Arduino/Teensy board connected to a stepper-motor driver integrated circuit.

2.3.3 Linear Controls

At the fine scale of linear motion one has piezo-electrics, which after being applied a suitable constant (DC) voltage they change their dimensions by as little as a few nanometers. A piezo-electric stack of about 10 mm (see for example Thorlabs model PC4QM) can be placed as a spacer in a translation stage for changing the path-length difference in an interferometer. A maximum travel of about $9 \mu\text{m}$ allows for a scan with 10 or so interference fringes. The piezo-electric requires a voltage in the range 0-150 V. To drive it with a computer, which can output only up to a few volts, we must add a voltage amplifier. One can use an inexpensive solid-state amplifier, such as EMCO model Q02-24, or alternatively, a standard voltage amplifier instrument. We use both in our labs. The best way to drive it is to use an Arduino/Teensy board that can put out either a 0-5 V DC, or drive a digital to analog integrated circuit, such as LTC1257, which accepts a digital number serially and outputs 0-9 V analog. That output was amplified and applied to the piezo-electric element.

For the coarse linear motion there are mechanical motor-driven fine screws. Commercial products include encoders and interfacing options. We used these types of actuators in the delayed-choice experiment to change the path-length difference of an interferometer by an amount that is greater than the coherence length of the light with a broad bandwidth (e.g., 40 nm for down-converted photons). We also used an-house stepper-motor to turn a threaded rod, which in turn slid an optical mount in and out of the path of the photon beam.

3. OUR RECENT EXPERIENCE WITH THREE REMOTE EXPERIMENTS

We did 4 remote labs in our most recent lab experiences: Stern-Gerlach-type polarization projections, the quantum eraser, the delayed-choice experiment, and polarization entanglement. All used the webcam and the

on/off control for the laser and detectors. The quantum eraser and delayed-choice used the piezo-electric for scanning the interferometer phase. The quantum eraser used two rotation mounts, one to rotate a waveplate (similar to Fig. 4(a)) and another one to insert a polarizer in the path of one of the photons (similar to Fig. 4(b)). The delayed-choice experiment used one rotational mount to switch filters placed in the path of one of the photons (as in Fig. 4(b)). It also used a motorized linear stage to change the path length by coarse amounts (to about 80 μm in increments of 5 μm). The experiment on entanglement used 3 rotational mounts, two to rotate waveplates (shown in Fig. 4(a)) and a third one to insert a quartz plate in the path of one the photons (similar to Fig. 4(b)). The photon Stern-Gerlach experiments used motorized rotation stages for a polarizer and a half-wave plate plus linear and angular placing of additional components in and out of the path of the photon beam. The angular placement of an optical mount is shown in Fig. 4(c).

4. DISCUSSION

This manuscript presents the mechanics of remote upper-level physics labs that we offered to our students at Colgate University.¹² Students were able to perform the labs successfully. The use of devices connected by the USB serial port are quite convenient and easy to use. In our case we used Matlab as a platform to acquire data. However, other platforms such as Labview or Python are equally viable depending on the local expertise. There are other electromechanical options that could be incorporated. The Arduino/UNO platform can also be used to read various sensors to provide useful redundancies.

A remote apparatus provides additional instructional possibilities. One can give students only clues about the experiment they should perform so that they have to make decisions on what to measure and how to measure it. They can be asked to make a derivation based on the setup and make a prediction, to then test the prediction using the tools available, but following a procedure designed by them. In addition, a remote lab could also be a platform to solve problems remotely, where the students are challenged to resolve a situation where they have to use the sensors and actuators to understand a situation and overcome a problem.

Finally, remote labs can provide a new paradigm for labs. Because labs depend on a physical location where students and the instructor congregate to carry an experiment, lab sections have to be scheduled as an add-on component of the instruction. However, with remote labs we remove the need to create such a section, because the students can do the lab at flexible times. Thus, labs can become take-home assignments, where students do them in their own time. The remote option may also remove the need to have multiple copies of the same apparatus, with student groups working on a single setup in a sequential manner. Communication with the instructor can be online or utilizing modern chat groups.

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APPENDIX A. ARDUINO-BASED CONTROL CIRCUIT

The Arduino-board-driven circuit mentioned above provided power to relays that controlled the power to the laser and detectors. This circuit driven by the Arduino-UNO board is shown in Fig. 5. A high (+5 V) output of a digital line drives the transistor making it act as a switch. When it is driven this way, the 12-V power is applied to the coil of the relay, which in turn closes a mechanical switch providing power to the desired device.

The Arduino program is always running in an infinite loop. The associated serial window is shown in the lower-left portion of the desktop view of Fig. 3. The command is entered on the top line of the window. The action taken is listed in the lower part of the window. A summary of commands is given below.

- **Laser ON (Unblocked):** This action is enabled by entering “1”. There is a visual verification that this action took in place: the beam scatters light from at least the down-conversion crystal, and this is seen in the webcam window.

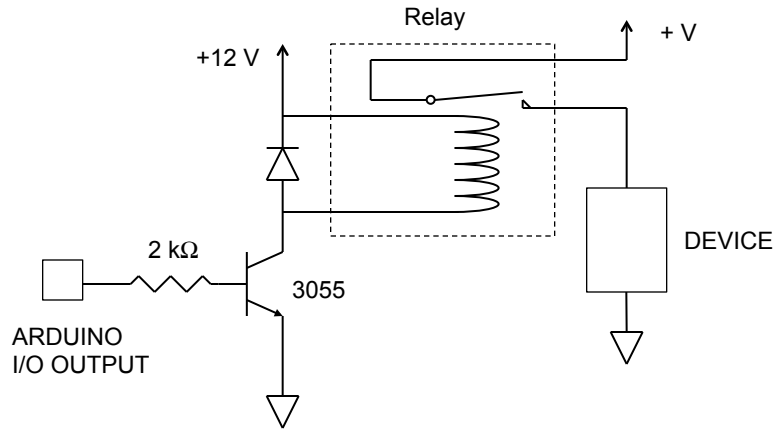


Figure 5. Circuit to power devices remotely. Its input is connected to an I/O line of an Arduino-UNO board. The activated relay provides power to the device.

- **Laser OFF (Blocked):** This action is enabled by entering “2” . It must be done at the end of the lab session.
- **Detectors ON:** This action is enabled by entering “3” . This action should be verifiable. One can either use a digital readout of the voltage applied to the detectors and viewed by the webcam, as shown in Figs. 1 and 2. This voltage should be close to 5 V. Alternatively, one can input the detector voltage to an analog voltage input of Arduino, and read its value.
- **Detectors OFF:** This action is enabled by entering “4” . Must be done at the end of the lab session.

The Arduino program is a simple one: the user enters a numbered option through the serial monitor platform of the Arduino board. Parts of the program contained in an infinite loop are shown below. By pushing different numbered keystrokes the user controls whether they are on or off. The I/O lines for the laser and detectors are #4 and #5, respectively. The input value is assigned to the variable “onoff.”

```

Serial.println(" Laser 1=ON, 2=OFF:");
Serial.println(" Detectors 3=ON, 4=OFF:");
:
if (onoff == "1") {
digitalWrite(4, HIGH);
Serial.println("Laser ON");}
if (onoff == "2") {
digitalWrite(4,LOW);
Serial.println("Laser OFF");}
if (onoff == "3") {
digitalWrite(5, HIGH);
Serial.println("Detectors ON");}
if (onoff == "4") {
digitalWrite(5,LOW);
Serial.println("Detectors OFF");}

```


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