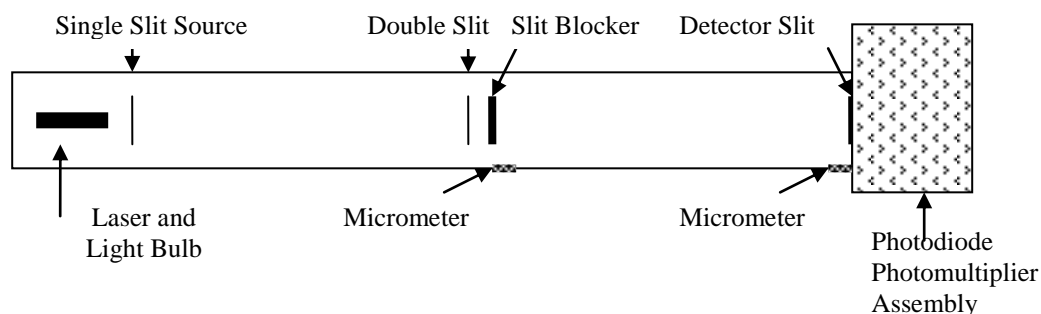


A Conceptual Tour of TeachSpin's Two-Slit Interference, One Photon at a Time

The apparatus consists of a U channel a little over a meter in length with a light tight removable cover. At one end the student can use either a laser or a small bulb. At the other end is a detection system which contains both a photodiode and a photo multiplier.



Just in front of the light source is a single slit which we call the *single slit source* because it is the source of the photons for the two slit interference pattern. The central maximum of the single slit pattern is adjusted so that it falls on the *double slit*, a pair of slits fifty centimeters along the channel. A moveable *slit blocker* is on the far side of the double slit. The blocker can be set to allow light from either or both slits to proceed down the channel. The slit blocker is manipulated with a micrometer mounted on the outside of the U channel. At the far end of the U channel is a moveable single slit we call the *detector slit*. The detector slit can be moved across the face of either the photodiode or photomultiplier. This, too, is attached to an external micrometer which monitors its location.

The laser is mounted in front of the bulb in such a way that it can be moved out of the way without being removed from the apparatus. Here is an experimental order we think sensible.

A. Demonstrating that photons move singly and independently through the single slit and down the length of the apparatus. (If time is an issue, this part of the experiment can be done as a demonstration or simply described.)

1. With the light source off, open the system, and make sure the laser is out of the path of the bulb.
2. Place a single slit in position just in front of the light source. This becomes your Single Slit Source. Make sure that the double slit, slit blocker, and detector slit have been removed. Now all of the photons coming through the slit in the solid arc defined by the single slit and photomultiplier surface will be counted. Notice the narrow band green filter mounted in front of the bulb. As the brightness of an incandescent bulb, such as the one we are using, is decreased, the color spectrum shifts to the red. The light intensity in the green region drops dramatically and only one green photon at a time proceeds down the channel to the photomultiplier.
3. Install and secure the cover. The protective default system now allows the photomultiplier to be activated.

4. Leave the shutter, which keeps the light from the entering the photomultiplier, in place. Make sure the toggle for the light sources is in the Bulb On position and begin to turn up the high voltage on the photomultiplier. (**The high voltage will not operate with the light source toggle set to off!**)
5. Even with the shutter closed, the photomultiplier (PMT) will show counts. This is the “dark current” due to random electron emission within the photomultiplier itself.
6. The photomultiplier operating voltage and the discriminator threshold voltage are both adjustable parameters. They must be set so that the PMT will optimally count green photons and optimally reject the dark current. (This can be done by the instructor or can be an opportunity for students to learn how to use a photomultiplier for proper photon counting.)
7. Make sure the counter you are using is set in the kHz range. With the bulb intensity at about half of maximum, open the shutter to expose the face of the photomultiplier. The count rate will be on the order of 50 kHz which is 50×10^3 photons/second. For the green wavelength of interest, the PMT is about 5% efficient; it counts only about 1/20 of the green photons. Therefore, the total rate at which photons are actually reaching the PMT must be $20 \times 50 \times 10^3$, or about 10^6 photons/second. That’s one million photons per second. How could that be one photon at a time?
8. What if we could arrange the photon emissions so that as one photon arrived at the photomultiplier, the next one would just be coming through the single slit? At that rate, not only would there be only one photon arriving at a time, there would even be only one photon in the channel at a time. For this condition, what count rate would come from the photomultiplier?

Any individual photon traverses the 0.9 meter distance from the single slit to the PMT a speed of $c = 3 \times 10^8$ m/s, spending a time of only 3×10^{-9} seconds or about 3 ns, in flight. With 3 ns between photon arrivals there will be 3×10^8 photons per second reaching the detector. Now since one million is 10^6 , we are talking about 300 million photons per second reaching the detector using our constraint. That is 300 times as many photons as we actually observe!

9. This means that for 1/300 of the time we were “watching” there was “one” photon in the channel, the rest of the time, 299/300 of the time, there were “no” photons in flight. The probability of there being two photons in flight simultaneously is quite negligible. The interference effects observed in this apparatus can thus be ascribed to the behavior of individual photons, coming through the single slit one at a time!

B. Aligning the System and Performing a Quantitative Young's Experiment

1. With the system open, move the laser so that it is front of the light source. Put the double slit, slit blocker and detector slit in position and turn on the laser. Adjust the single slit source and the double slit until the central maximum of the single slit pattern covers the double slit. A card placed just behind the double slit/slit blocker assembly will show a pair of thin red lines of laser light. The double slit and slit blocker masks are then adjusted to make the slits vertical.
2. With the card still in place, the micrometer is used to move the slit-blocker until one slit is blocked. The slit-blocker must be adjusted so that its opening is parallel to the double slits. When the slits and the slit blocker opening are properly aligned, one of the thin red lines will disappear all at once. Using the micrometer, the slit-blocker can be moved to locate five key readings: both slits blocked, only the far slit open, both slits open, only near slit open and both slits blocked with slit-blocker now closer to near side.
3. The characteristic two slit pattern of the laser can easily be seen on a small white card placed in front of the detector slit.
4. Now the detector slit must be aligned visually so that it is parallel to the two slit pattern.
5. With the laser on and the photomultiplier shutter down, the channel is closed and the photodiode is used to make a quantitative investigation of the pattern. The photodiode section of the Photon Counting Module acts as a current-to-voltage converter. A voltmeter connected to the Photodiode Output provides relative intensity readings. Moving the detector slit across the face of the photodiode gives the intensity pattern as a function of micrometer reading. If the alignment is good, meaning that the detector slit is parallel to the openings of the two-slit array, the voltmeter reading (and thus the light intensity) of the central maximum is at least ten times higher than that of its nearest minimum. (See graph of Photodiode Voltage vs. Location in the Two-Slit brochure or web page.).

C. Two-Slit Interference, One Photon at a Time

Having verified that only one photon at a time is coming through the single slit, checked the alignment of the slits, and observed the characteristic two-slit interference pattern of the laser, it is time to see what the single photons will do.

1. Open the Channel and move the laser to the side. Make sure the switch of the high voltage of the Photon Counting Module is in the off position, and the potentiometer is turned to zero.
2. Move the **light source switch to the Bulb On position** and set the light bulb intensity about half way. The high voltage and discriminator settings should be adjusted as directed. Now the photomultiplier shutter can be opened.

3. Set the frequency counter to give the number of counts in 10 second intervals and, using the micrometer, slowly vary the location of the detector slit. A graph of photon count for 10 second intervals vs. location of the detector slit reveals the same general interference pattern observed with the photodiode. The spacing between the maxima, however, indicates that this pattern is due to green photons rather than the red ones from the laser. If Cricket is being used, students actually “hear” the change in the photon count before the counter registers. (See the graph which shows the photon counts per 10 second interval vs. location).
4. Another interesting activity is to locate the detector slit at a place which gives a minimum count rate for two slits and move the slit blocker to see what happens when one slit or the other is blocked. If you have two faucets and turn one off, the flow rate cuts in half. What happens here?

There are several noteworthy aspects of the design.

Careful fail safe systems protect the photomultiplier. Among other things, the photomultiplier and its high voltage source get no power unless the light tight cover is secured and the light source indicator is in the “Bulb” position.

The entire photomultiplier/photodiode assembly can be detached from the U channel so that it can be used in other experiments. We felt this was too versatile (and too expensive) a component to have it locked into just one experiment.

As always, with TeachSpin apparatus, students are able to explore many aspect of the instrument. They can study the photon counts from the dark current of the photomultiplier as a function of voltage and then look at readings from the light bulb at low intensity, as a function of voltage. While the dark current pattern is linear, the low intensity light signal saturates. Interpreting these graphs helps students to understand both how photomultipliers work and how to choose the optimal operating and threshold voltage settings for this particular experiment.