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Two Slit Interference, One Photon at a Time

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With TeachSpin's TWS1-A, students confront the "mystery" of wave-particle duality by comparing the results of visual, photodiode and photomultiplier observations of interference patterns generated by the same optical path. With the system open, they can use a white card placed at the far end of the U-channel to make naked-eye qualitative observations of an interference pattern cast by the laser. Closing the system, they can use a photodiode to make quantitative measurements of light intensity as a function of position for the interference pattern they have just been looking at. Most dramatically, they can explore, quantitatively, the relative rate of photon arrival as a function of position across the same region.

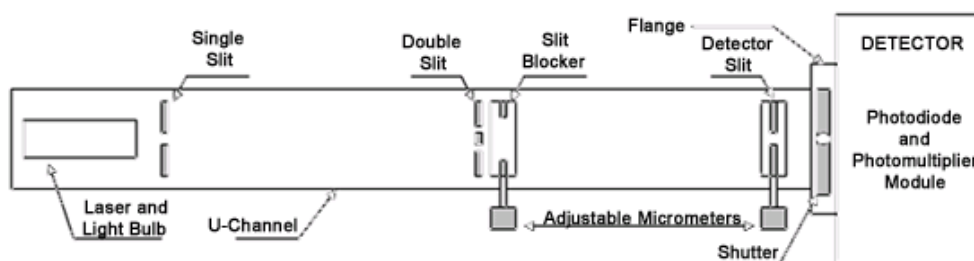


Figure 1: Schematic Diagram of U-Channel

Qualitative Observations and Calibration of the Micrometers

With the system opened and using the laser, the student adjusts the single and double slits to make sure they are properly aligned. A viewing card placed just behind the double slit/slit blocker assembly shows a pair of thin red lines of laser light. Now the reading on the micrometer for both slits blocked, only left slit open, both slits open, and only right slit open can be determined.

In subdued light, interference patterns can easily be seen on a small white card placed in front of the detector slit. While learning to use the slit blocker, they can easily see distinct differences between the interference patterns from single and from double slits. These observations are essential for a clear appreciation of the sets of measurements taken when the cover is closed and the apparatus appears more like a "black-box."

Measuring Light Intensity as a Function of Position

With the laser on, the system is closed up and the photodiode placed in the optical path. The photodiode is connected to a voltmeter through a current-to-voltage converter. The student moves the detector slit across the face of the photodiode and records the output voltage (which is proportional to the light intensity) as a function of micrometer reading. Here, we want the student to get a quantitative record of what was observed visually.

In Figure 2 below we show the data obtained in this realization of Young's classic experiment. The lines are drawn merely to guide the eye.

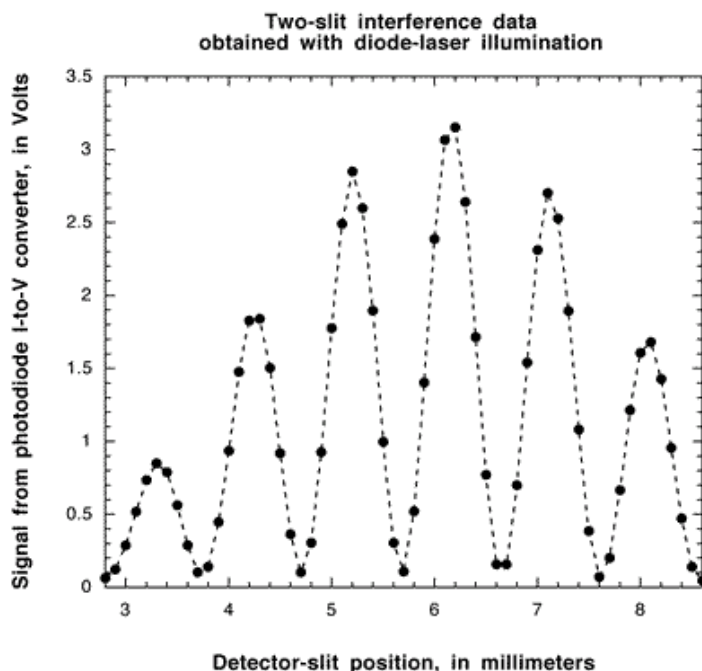


Figure 2: Light Intensity vs Position for Laser Two-Slit Interference Pattern

These data can be compared to different theoretical models of the two-slit phenomenon. The simple Fraunhofer model reproduces most of the major features, but the more sophisticated Fresnel integral or Feynman's "sum over paths" can give students greater depth of understanding. Both are carefully discussed in the instructor's manual.

Creating a Single Photon Source

As anyone who has ever used a light dimmer can attest, decreasing the light output of a given incandescent bulb shifts the spectrum toward the longer, red wavelengths. By placing a narrow band green filter in front of a standard light bulb, students use this "obvious" phenomenon to create a source of single photons.

The system is opened, the laser turned off and the bulb lifted into place. The double slit, slit blocker, and detector slit are removed. Now a very narrow band green filter is slid into place in front of the bulb. As the bulb intensity is turned down, the color spectrum shifts to the red, the light intensity in the green region drops dramatically and one photon at a time passes through the single slit. (This works better than neutral density filters.)

The top is now put on and secured which allows the photomultiplier to be activated. The shutter which keeps the light from entering the photomultiplier is still kept in place. The bulb intensity is set to about half of maximum.

Optimizing the Photon Counting Unit

In the photomultiplier both the high-voltage (operating voltage) and the pulse-height discriminator threshold voltage must be properly selected to optimize the operation of the photon counting unit. They must be set so that the photomultiplier 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.)

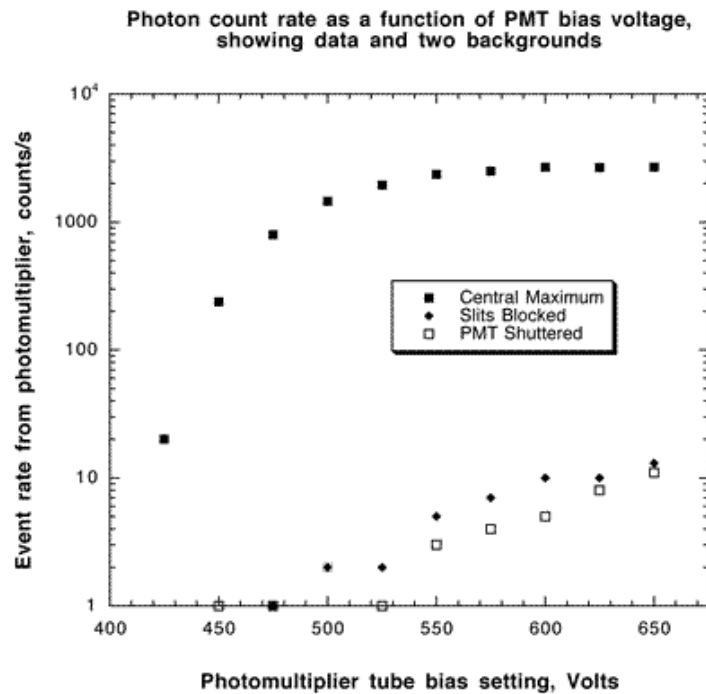


Figure 3

With the discriminator level fixed, both the count rate for dark current (photomultiplier shutter closed) and the count rate for "green" photons can be measured as a function of photomultiplier high-voltage. While the dark current pattern is linear, the low intensity signal saturates. Interpreting these graphs leads to an understanding of how a photomultiplier works and to how to set the operating and threshold voltages.

The data shown in Figure 3 indicates that a setting near 550 V is optimal.

Interpreting the Data to Validate Single Photon Production

With the photomultiplier shutter open, students use a frequency counter to find the rate at which photons are coming through the single slit. The photomultiplier readings will be around 50×10^3 photons/second. Since photomultiplier is rated at 5% efficiency, the actual photon arrival rate is 20 times greater, 1000×10^3 or 10^6 photons/second.

It is here that students must convince themselves that this counting rate indicates the bulb is indeed dim enough so that only one photon at a time reaches the photomultiplier. Here are two possible conceptual arguments, both use the fact that the distance from single slit to detector is close to one meter.

1. Using time of flight measurements: A photon traveling 3×10^8 m/s will navigate the one meter path from single slit to detector in roughly 3 nanoseconds. Our counter indicates a time of flight of 10^{-6} seconds or 1000 nanoseconds. On average, therefore, there is a photon in flight between the single slit and the photomultiplier for only about 3 ns out of every 1000 ns. This means that for 99.7% of the time, there are "no" photons in flight, while for only 0.3% of the time there is "one" photon in flight in the apparatus. The probability of there being two photons in flight simultaneously is thus negligible. All of the interference effects observed in the apparatus can thus be comfortably ascribed to the behavior of individual photons, coming through the single slit one at a time!

2. Using frequency measurements: The flight path is roughly one meter. If we were to visualize an arrangement such that a new photon would be released only after the one in transit arrived at the photomultiplier then the photons would be 1 meter apart. This would mean that the time between photons would be

$1\text{m}/3 \times 10^8\text{m/s}$. The photon count rate would then be 3×10^8 photons per second. The photomultiplier will show around 50×10^3 photons/second. The photomultiplier is rated at 5% efficiency so this means that the actual photon arrival rate is 20 times greater or 1000×10^3 photons/second. We are getting only 10^6 photons/sec which means that the photons act as if they are 100 meters apart.

Observing the Result of Single Photon Interference

Once students have convinced themselves they will be getting one photon at a time, they close the photomultiplier and reopen the channel. Now they must reinsert the double slit, slit blocker and detector slit, and check their alignment.

The system is again closed and the photomultiplier shutter opened. With the discriminator output connected to a frequency counter, students determine counts in 10 second intervals at various locations of the detector slit. Data for the three possible positions of the slit blocker are shown below. The graph of photon counts vs. detector-slit location for two-slits open reveals the same general interference pattern observed using the laser and photodiode. The slightly closer spacing of the maxima shows that we are now looking at green photons rather than the red ones from the laser.

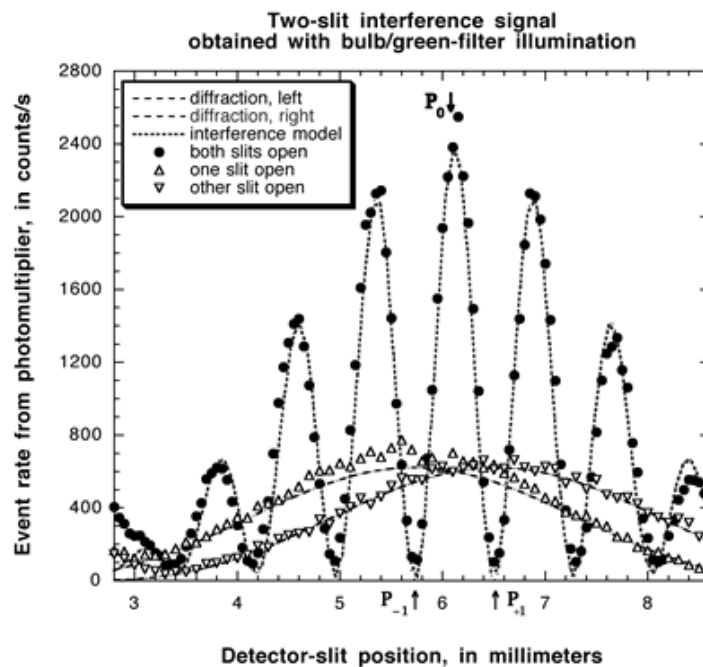


Figure 4: Photon Counting Data for Single and Double Slit Configurations

A Dramatic Demonstration of the "Essential Quantum Paradox"

The "essential quantum paradox" can be shown dramatically by a simple experiment. The detector slit is positioned, in turn, at the three empirically determined positions of the -1 minimum, the central maximum, and the +1 minimum of the interference pattern, marked in Figure 4 as P_{-1} , P_0 , and P_{+1} . Photon count rates are measured for the slit-blocker set to permit light to pass through only one slit, through both slits, or through only the other slit. Data is shown in Figure 5.

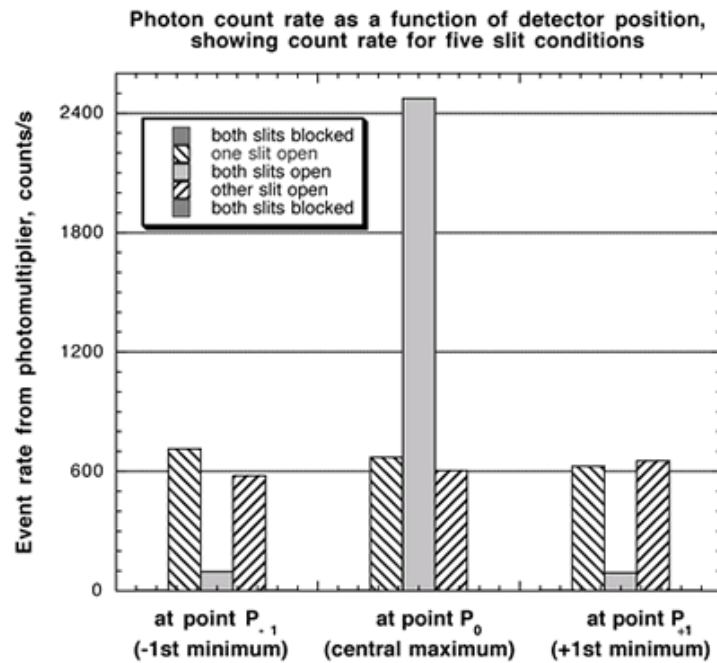


Figure 5: Comparative Photon Counts Demonstrate the Quantum Paradox

At the central maximum, going from one to two slits *quadruples* not doubles, the count rate. And, contrary to the logic of classical particles, at either minimum, opening a second slit markedly *reduces* the count rate.

An extension

As always, TeachSpin instruments lend themselves to expanded investigations. By injection of a TTL signal, the diode laser can be modulated so that lock-in detection of the photodiode signal becomes possible. Because of the noise rejection of lock-in detection, sensitive quantitative measurements of the laser-light interference signal can be achieved, even with the U-channel uncovered. TeachSpin's Signal Processor/Lock-In Amplifier is ideal for making these measurements.

Learn about [Two Slit's Cricket](#).