TeachSpin's Two-Slit Interference, One Photon at a Time
A Conceptual Introduction to the Experiment

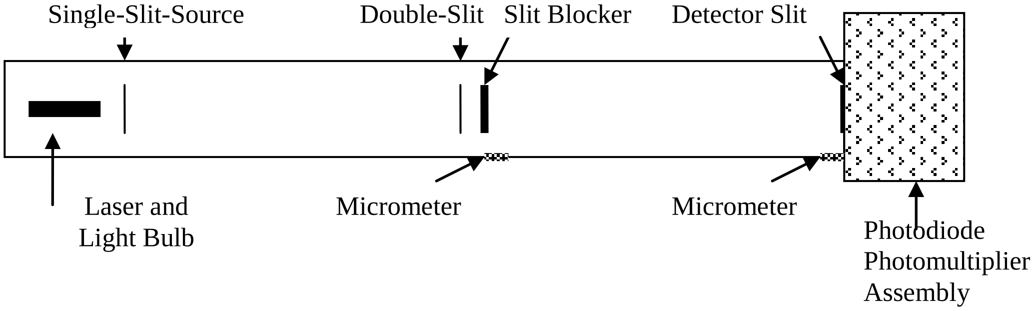
Pick up any book about quantum mechanics and you're sure to read about 'wave-particle duality'. What is this mysterious 'duality', and why should we believe that it's a feature of the real world? How can light act like waves and yet arrive as particles? To Richard Feynman, this paradox is the fundamental issue of quantum mechanics. He calls it:

> a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by explaining how it works. We will just *tell* you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics." [R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, vol. I, ch. 37, or vol. III, ch. 1 (Addison-Wesley, 1965)]

With this apparatus you will perform the famous two-slit interference experiment with light, first with the intense light of a laser, and then at the limit of light intensities so low that you can record the arrival of *individual photons* at the detector. And that brings up the apparent paradox that has motivated the concept of duality -- in the very interference experiment that can be used to measure the wavelength of light, you can monitor the arrival of the energy of light in particle-like quanta, in individual photon events.

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 as a light source either a laser or a small bulb. The laser is mounted in front of the bulb in such a way that in can be moved out of the way without being removed from the apparatus.

The module at the other end houses a pair of detection systems. The student can use either a photodiode to measure the intensity of laser light or a photomultiplier tube (PMT) to record individual photon arrivals.



Just in front of the light sources is a single slit which we call the ***single-slit-source*** because acts as the source of either the laser or bulb photons, which later create the two-slit interference pattern. The central maximum of the diffraction pattern created by the single-slit-source is adjusted so that it falls on the ***double-slit***, a pair of slits located 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 interference pattern to let the light from a selected location fall onto either the photodiode or photomultiplier. This, too, is attached to an external micrometer which controls its location.

The key to the experiment is the green filter which covers the incandescent light bulb. When the bulb is used on low current, the color of the light becomes very red. The production rate of green photons, therefore, drops dramatically and allows detection of individual photon events!

But, under what circumstances can we claim that the apparatus is running in the mode of 'one photon at a time'? Under typical operating conditions - using the bulb source with the green filter in place, the source-slit present, both double slits open, the detector-slit on the central maximum, and bulb-intensity dial at half-scale - we get about 10^3 photon events per second at the PMT. But to count *all* the candidate photons in the box, we must remove the double-slit and detector-slit structures, and count the total rate at which photons reach the PMT from the source slit. *We find about 10^6 photon events per second* under these conditions. So that says there's another photon emerging from the single-slit source every 10^{-6} s = 1 μs, on average. And, since the photon source is thermal, the photons can be assumed to emerge at random and independently of each other. This might sound like a high rate of photon arrivals, but consider that the time-in-flight of any photon in the box is of order (length)/ c ≈ (1 m) / (3 x 10^8 m/s) = 3 x 10^{-9} s = 3 ns = 0.003 μs. Just *one photon at a time in the box, would give a count rate on the order of 3 x10^8 photons/second.* So the picture to have in mind is that 99.7% of the time, there are no photons in flight, and that about 0.3% of the time, there is one photon in flight. Insofar as the photons emerge independently of each other, the probability that there will simultaneously be *two* photons in flight in the box is less than 0.001%.

Now we turn to some of the experiments that can be done.

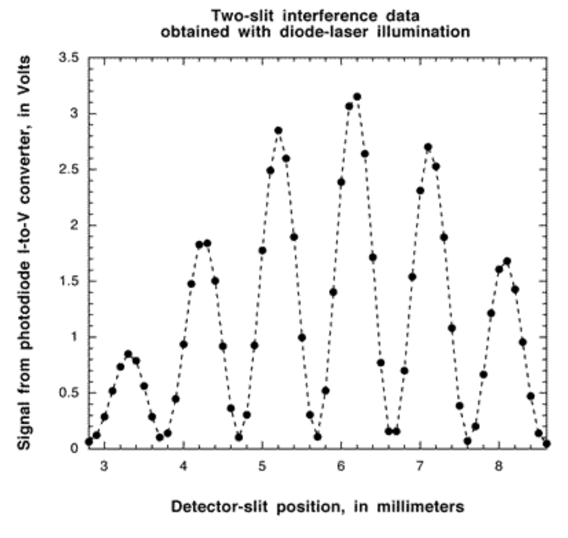
1. Using the laser, two-slit interference can be observed *visually*, by opening up an apparatus and seeing the exact arrangements of light sources and apertures which operate to produce an 'interference pattern'. It is important to examine every part of the apparatus and make all the measurements you'll need for theoretical modeling. Be sure to record the reading on the slit-blocker micrometer for five key positions: slit-blocker in the far position with both slits blocked, only the far slit open, both slits open, only the near slit open, and both slits covered with the blocker at the near position.
2. The classic Young's experiment can be performed *quantitatively*, recreating not only Young's measurement of the wavelength of light, but also getting detailed information about intensities in a two-slit interference pattern, which can then be compared to predictions of wave theories of light.
   a. From the slit spacing, the location of the components and the interference pattern we can find the wavelength of the light being used. Three sets of double slits are provided with center to center spacing, *d*, of 0.35 mm, 0.40 mm, and 0.45 mm. The micrometer allows us to measure Δ*x*, the distance between adjacent maxima. The distance, *L*, from the double-slit to the detector-slit/photodiode, where the interference pattern is being observed, is measured to be 480 mm. Because L is so much greater than Δ*x* we can calculate the wavelength of the red laser light using the familiar approximation:

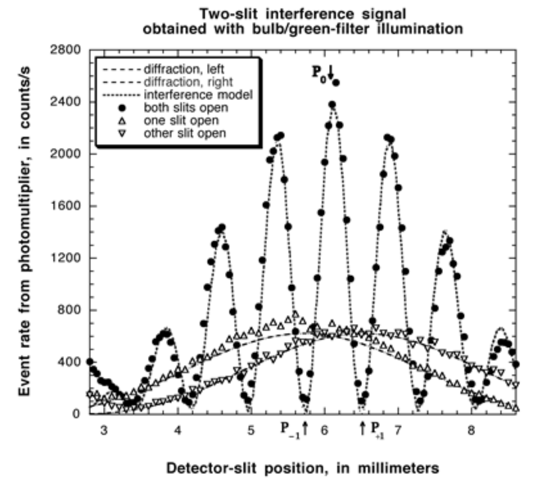
$$\frac{\Delta x}{L} = \frac{\lambda}{d}$$

   b. Another interesting investigation compares the *intensity* of light at the central maximum of the two slit pattern to the intensity of light at that location when only one slit or the other is open.

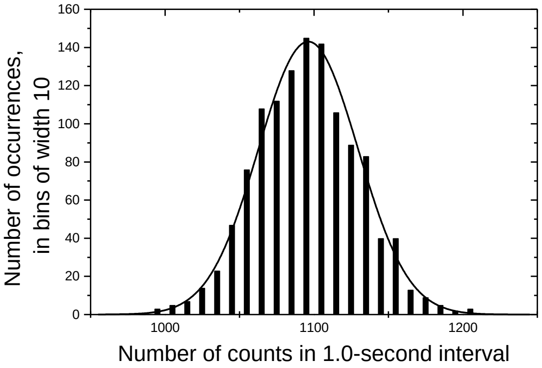
3. The two-slit experiment *one photon at a time* involves the same kind of experiments, but now at a light level so low that you can assure yourself that there is at most one relevant photon in the apparatus at any time. Not only will this familiarize you with single-photon detection technology, it will also show you that however two-slit interference is to be explained, it must be explained in terms that can apply to single photons. [And how can a single photon involve itself with two slits?]

The graphs below show both similarities and difference between the laser and photon patterns.





The new Pulse Counter/Interval Timer (PCIT), which can also be used with the original Two-Slit apparatus, allows us to do some interesting statistical investigations.



4. Using the PCIT in the automatic mode as a pulse counter, we can look at the variations in the number of photon counts per second at a single location of a two-slit pattern. The data is analyzed by creating 'bins' of counts and determining the number of times the counts in a given series of measurements fall into each bin. Because the production of photons is random, the bin count pattern fits into a classic Poisson distribution.

5. Using the interval timer function of the PCIT, we can look at the variation in time between photon arrivals. The resulting pattern will surprise you.