Double Slit Experiment: One Photon at a Time

Contents

Part I: Conceptual and Historical Introduction

A. Wave-particle duality

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? This manual describes the TeachSpin Two-Slit apparatus designed to make the concept of duality as concrete as possible, by letting you encounter it with photons, the quanta of light.

This apparatus makes it possible for you to perform Young's famous two-slit interference experiment with light, even in 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 makes possible the measurement of the wavelength of light, you will be seeing the arrival of light in particle-like quanta, in individual photon events. How can light INTERFERE like waves and yet arrive as particles? This paradox has been used, by no less an authority than Richard Feynman, as the introduction to the fundamental issue of quantum mechanics:

"In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine 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)]

You should find and read either of these famous chapters in the Feynman Lectures that introduce the central features of quantum mechanics using the two-slit experiment as an example. Feynman notes that he discusses the experiment as if it were being done with particles with rest mass, such as electrons. He also wrote in an era in which he was discussing a ‘thought experiment’. But since that time, the two-slit experiment really has been done with neutrons [see Reviews of Modern Physics 60, 1067-1073 (1988)]. In performing Two-Slit Interference, One Photon at a time, you too will translate a thought experiment into a real one, in this case with photons.

There are several technical advantages to the use of photons of visible light. They are easily produced and readily detected as individual events, using the ordinary tools of optics. They propagate freely in air and require no vacuum system. They are electrically neutral, and thus interact neither with each other nor with ambient electric and magnetic fields. They are (at high enough levels) directly visible to the eye. Finally, their wavelengths are of a much more convenient size than the available wavelengths of electrons or neutrons. All these technical advantages make it possible to perform even the single-photon version of the two-slit experiment in a tabletop-sized and affordable instrument.

B. Historical context

There is a rich historical background behind the experiments you are about to perform. You may recall that Isaac Newton first separated white light into its colors and, in the 1680's, hypothesized that light was composed of ‘corpuscles’, supposed to possess some properties of particles. This view reigned until the 1800's, when Thomas Young first performed the two-slit experiment now known by his name. In this experiment, he discovered a property of destructive interference, which seemed impossible to explain in terms of corpuscles, but which is very naturally explained in terms of waves.

Young’s experiment not only suggested that such ‘light waves’ existed, it also provided a numerical result for the wavelength of light, measured in familiar units. (He even showed that the measured wavelength correlated with the subjective color of the light used.) Light waves became even more acceptable with dynamical theories of light, such as Fresnel’s and Maxwell’s, in the 19th century, until it seemed that the wave theory of light was incontrovertible.

The discovery of the photoelectric effect, and its explanation in terms of light quanta by Einstein, threw the matter into dispute again. The explanations of blackbody radiation, of the photoelectric effect, and of the Compton effect seemed to point to the existence of ‘photons’, quanta of light that possessed definite and indivisible amounts of energy and momentum. So successful have these models become that the modern ‘photon’ or quantum-of-light might seem to be Newton’s corpuscle brought back to life.

The difficult thing to realize is that, whatever light might actually be, it still displays all those phenomena which gave support, in the 19th century, to wave interpretations. That is to say, even if light is ‘composed of’ photons, it still displays Young’s two-slit interference phenomena. So does light have a dual nature, of waves and of particles? And if experiments force us to suppose that it does, how does the light know when to behave according to each of its natures? These are the sorts of questions that lend a somewhat mystical air to the concept of duality.

Of course, the deeper worry is that the properties of light might be not merely mysterious, but in some sense self-contradictory. You will be confronted with just the sort of evidence which has led some scientists to worry that our theories for light, or at least our pictures of light, are not only surprising but also inconsistent or incoherent. As you explore the phenomena, keep telling yourself that the light is doing what light does naturally. And keep on asking yourself if the difficulties lie with light, or with our theories of light, or with our verbal, pictorial, or even mechanical interpretations of these theories.

C. Goals for this experiment

It is the purpose of this experimental apparatus to make the phenomenon of light interference as concrete as possible, and to give you the hands-on familiarity which will allow you to confront duality in a precise and definite way. When you have finished, you might not fully understand the mechanism of duality – Feynman asserted that nobody really does – but you will certainly have direct experience of the actual phenomena that motivate all this discussion.

Here, then, are the goals of the experiments that this apparatus makes possible:

1. You will be seeing two-slit interference visually, by opening up an apparatus and seeing the exact arrangements of light sources and apertures which operate to produce an 'interference pattern'.

2. You will be able to perform the two-slit experiment quantitatively. In addition to recreating Young's measurement of the wavelength of light, you will get detailed information about light intensities in a two-slit interference pattern that can be compared to predictions of wave theories of light.

3. You will be able to perform the two-slit experiment one photon at a time, continuing 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?]

4. You will be exploring some theoretical models that attempt, at differing levels of sophistication, to describe your experimental findings. You will thus encounter the distinctions between Fraunhofer and Fresnel diffraction theories in a concrete case and, in addition, learn the difference between a mathematical, and a physical, description of what is going on.

Part 2: Parts Description, Settings and Connections

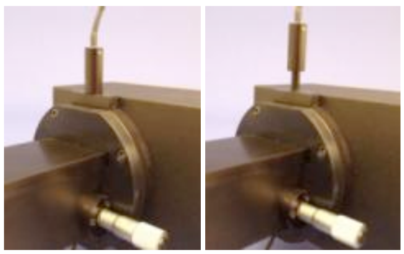
The double-slit apparatus has two light sources (a laser and an incandescent bulb) and two detectors (a solid state photodiode and a photomultiplier tube):

1. The laser produces a bright interference pattern that can be seen with the eye. When the laser is used, the double-slit apparatus is essentially operating in the classical limit (the light intensity is so high that the particle nature of light is not noticeable). To make quantitative measurements, a solid state photodiode is used to measure the light intensity (the photodiode works through the photoelectric effect.).

2. The dim incandescent light bulb is used in conjunction with a green narrow-band filter, which passes only a very small fraction of the photons emitted from the bulb. As you will see, this setup limits the photon production such that statistically, only a single photon is present in the apparatus at a time. In order to detect and amplify such a dim signal, a photomultiplier tube (PMT) must be used. Because this detector can be damaged if it is exposed to bright light, a shutter is employed to block the light to it when either the laser is used or when the top of the U channel is open (see caution below). ***Never open the U channel with the shutter open!***

Caution!!

Before Beginning: Make sure that the shutter separating the photomultiplier from the U-channel is securely **closed** by pushing down on the thick part of the cylindrical projection which emerges from the top of the flange of the AMPLIFIER MODULE. Then, you can remove and set aside the cover of the long U-channel assembly.



CLOSED OPEN

Figure 1: Shutter Positions

The descriptions below assume that the TWS apparatus is fully assembled with the wooden feet and the AMPLIFIER MODULE attached. The apparatus should be in front of you with its ‘source end’ to your left and the ‘detector end’, the AMPLIFIER MODULE, to your right (see Figure 2).

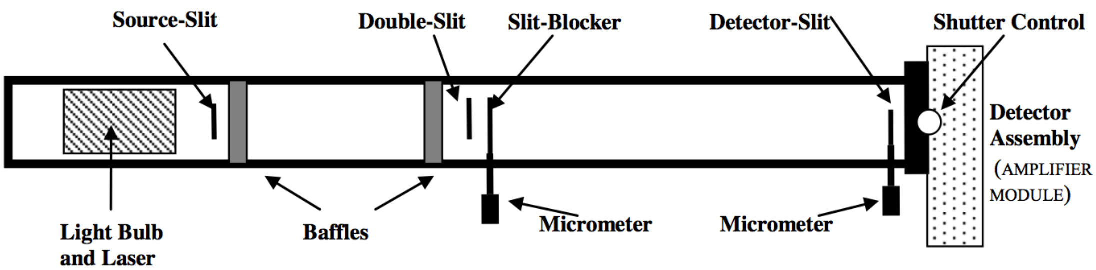


Figure 2. **Schematic of TWS apparatus - not to scale**

Settings and Connections

Shutter Closed

1. Make sure the shutter is CLOSED. Remove and set aside the cover of the long U-channel assembly. Visually inspect the apparatus and use Figures 2 and 3 to identify the bulb assembly, laser assembly, baffles, source slit, double slit, slit blocker and detector slit.

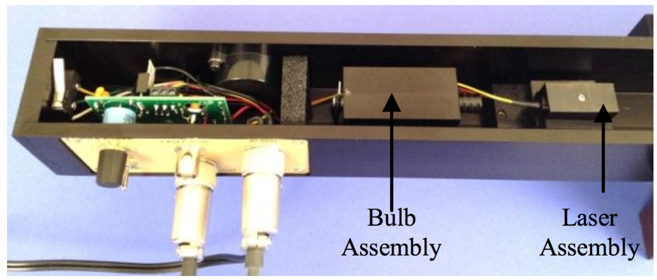


Figure 3: Source end of the open U channel

2. Initial settings

   a. At the source end, set the source switch to OFF and turn the BULB POWER to its minimum value (counterclockwise).

   b. At the detector end, set the 10-turn HIGH VOLTAGE dial to ZERO and set the HIGH VOLTAGE toggle switch to OFF.

3. Check the cable connections

   a. A BNC cable should connect the top of the circular flange on the back of the AMPLIFIER MODULE to the INPUT of the CURRENT-TO-VOLTAGE CONVERTER section of the AMPLIFIER MODULE (Fig. 4).

   b. A 2-pin connector should run from the bottom of the circular flange flange to the ALARM port on the light source panel (Fig. 6). (This connects a safety interlock in the detector's shutter assembly to the powering of the light sources.)

   c. The +15-V universal DC power supply (often called a wall transformer or a 'brick-on-a- rope') should be connected to the round 5mm DC INPUT on the light source panel. Plug in the DC power supply to the wall. A small green light on the power supply itself will show you that it is energized.

Part 3: Aligning the Laser and Slits

1. Start by sliding the laser toward you across its support block until it fits snugly into place against the near ‘shoulder’. This puts the laser approximately on the centerline of the U-channel.

2. Turn the source switch from OFF to LASER. A beam of red light should emerge. Put an alignment card into the channel to see the beam. Move the card to follow the laser beam along the length of the U-channel.

3. The laser beam should be centered on the source slit and should emerge from the other side. If it isn’t centered, carefully nudge the laser assembly slightly until the beam becomes centered. If it is way out of alignment, you may have to pivot the shoulder block by loosening the adjustment thumbscrew on the bottom of the U channel.

4. Check to see that the laser beam is centered on the double slits. If not, adjust the laser or double slit assembly.

5. Place your card just downstream from the double slit and slit blocker assembly. You should see two very closely space vertical lines. If you see no lines or only one line, you will need to adjust the slit-blocker micrometer screw. Turning the micrometer knob moves the blocker back and forth across the channel. By turning it, you should be able to block one, two or neither of the slits. Try it, and then adjust it so that light from both slits makes it through.

6. Align the slit-blocker so that it is parallel to the double slit assembly.

    a. Adjust the micrometer knob to watch one of the red ribbons appear and disappear as you dial the micrometer back and forth.

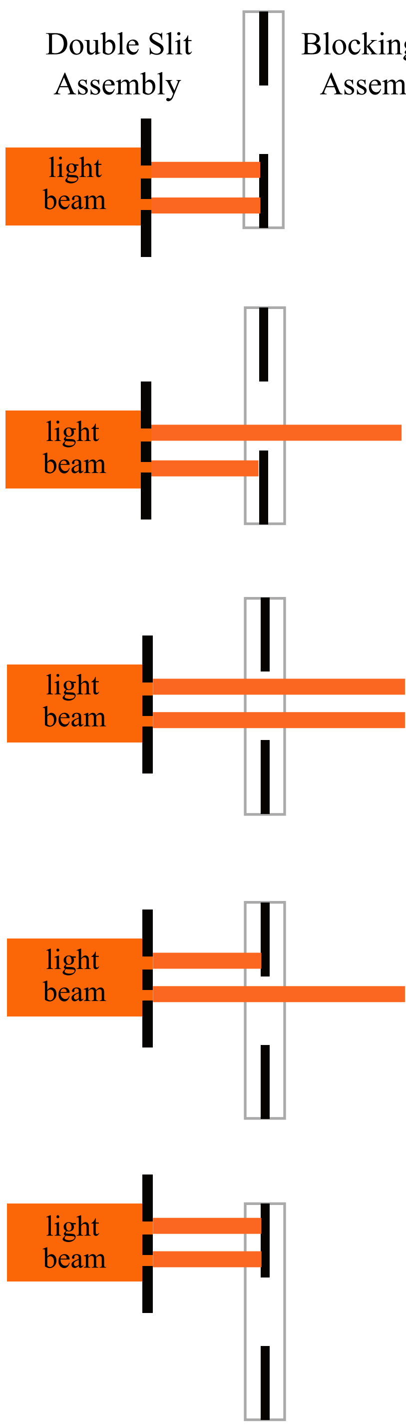
    b. If the slit-blocker’s edges are accurately vertical (and thus parallel with the pre-existing red ribbons), the light from one slit will go on and off ‘all at once’. But if the slit-blocker’s slit edges are not vertical, you’ll see the red ribbon’s disappearance start at one end of the stripe and then propagate vertically along the red stripe to completion.

    c. If you see this ‘partial eclipse’ sort of behavior, rotate the slit-blocker, i.e. lift one or the other of the top corners of the slit-blocker, by less than a millimeter and try this test again. You’ll have succeeded when you get the desired all-at-once extinction of a red ribbon of light.

7. The interference pattern should now be visible on the detector slit at the right end of the U channel assembly.

Part 4: Calibrate the Blocking Slit Micrometer

In the diagram below, the five positions of the slit-blocker are schematically depicted, showing how to block one or the other of the light beams emerging from the double-slits. From top to bottom, the slit- blocker moves 'downward' on the page relative to the double-slit. This corresponds to dialing the micrometer to larger readings as the shaft is turned counter-clockwise. It is wise to determine these five readings with the micrometer moving in only one direction to prevent errors caused by 'backlash'. Locate and record the micrometer readings for the following 5 positions:



1. With the micrometer turned far enough in, both beams will be blocked. You can use a reading in this range as a 'both slits blocked' setting.

2. If the micrometer is withdrawn just enough, you will unblock only the far beam of light. This is the 'far' version of the 'one-slit-only' setting.

3. Over a rather broad range, both beams of light come through the opening. Locations in this area are referred to as 'both-slits- open' or as 'both slits unblocked'.

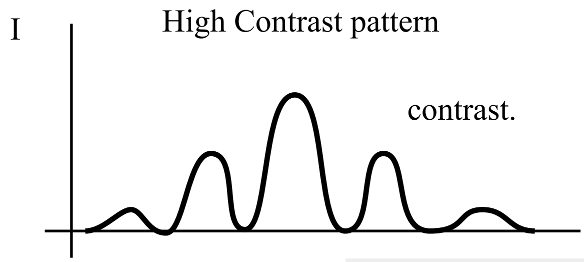
4. Continuing to turn the micrometer, you will find a location in which only the near beam of light is unblocked. This is the 'near' version of the 'one-slit-only' setting.

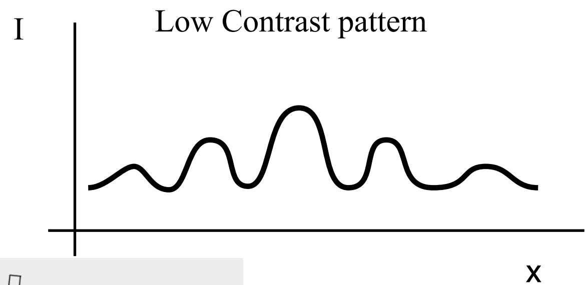
5. Finally, with micrometer far enough outward, both beams of light are again blocked.

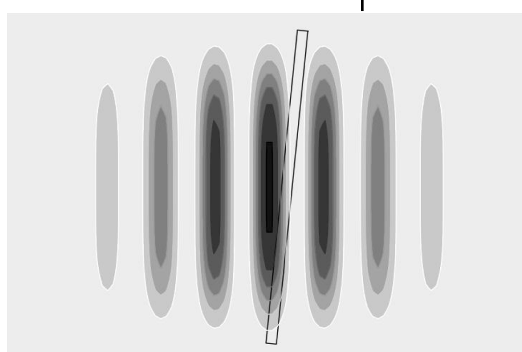
Part 5: Optimize Detector Slit Alignment

Under ideal conditions, the intensity of the light passing through the two slits will be identical and no stray background light will be present. In this case, the destructive zones will have zero intensity and the central peak will be strong (see left figure below). If one of the beams is stronger than the other, then they will not completely cancel out and only partial cancelation will occur. In this case the contrast of the pattern will be less than in the ideal case (see right figure). Note that the maximum height of the central fringe will also be diminished.

Another potential problem occurs when the detector slit is not parallel with the double slit. The detector slit will then be at an angle relative to the fringes (see below) causing a reduction in contrast.







A schematic face-on view of a fringe pattern and a mis-aligned detector slit. Because the detector slit is not parallel to the fringes, it cannot be located so that it will optimally overlap either a minimum or maximum in the pattern.

Proceed as follows:

Shutter Closed

1. Make sure that the shutter is CLOSED (see Figure 1). Closing the shutter to the PMT also positions the photodiode behind the detector slit. Connect a digital multimeter to read the potential difference appearing at the OUTPUT of the I-to-V converter (see figure below). Set the scale to 2-20 volts (DC).

2. To take measurements without closing the U-channel, place a piece of heavy black paper over the detector-slit section of the U-channel as shown in Fig. 4. We used a 3" x 5" strip and it worked well. You may need a longer one if the room is very bright. (see figure below)

Fig. 3 AMPLIFIER MODULE with I-to-V converter connected to multimeter

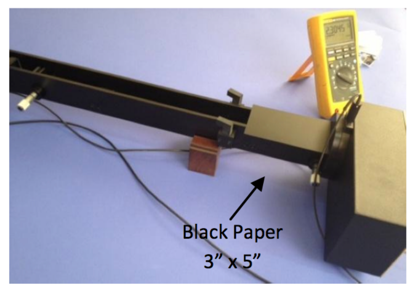


Fig. 4 System ready to take photodiode measurements

3. Set the slit blocker for two-slits open.

4. Adjust the detector slit micrometer so that the slit is positioned on the central fringe. This is most easily accomplished with the U channel cover off so you can visually align the slit.

5. Use the readings from the voltmeter to fine-tune the alignment. You want the maximum voltage. Record this value.

6. Now use the micrometer to locate a destructive zone. Record this value.

7. Block both beams and record the voltage. This voltage gives a measure of background light level. Ideally, the intensity in the destructive zone should equal the background level. Does it?

8. If the background level is not close to that of the destructive fringe, the detector slit might be slightly misaligned. Carefully rotate the detector slit slightly and remeasure the background, central constructive fringe and destructive fringe. Iterate this process until you are satisfied that you have achieved good contrast.

9. Replace the cover on the U channel and secure it with the four spring-loaded clips.

10. Measure and record the voltage values on the central peak with both slits open. Then close one slit, the other slit and both slits. Use the measurement with both slits blocked as the background value to subtract from the other measurements. Under ideal conditions we expect that $I_1 + I_2 = 4I_1$ (why?). You won't achieve this ideal, but hopefully you will show that $I_1 + I_2 > 2I_1$. Do you?

11. Repeat step 11 for the first destructive zone. In this case, we expect that $I_1 + I_2 = 0$.

Part 6: Switching to Bulb and PMT Mode

In this part you will switch from the laser/photodiode combination to the single photon bulb/ photomultiplier tube:

1. Preparing to switch to bulb:

    a. Make sure that the shutter is CLOSED (see Figure 1). Closing the shutter to the PMT also positions the photodiode behind the detector slit.

    b. On the AMPLIFIER MODULE, confirm that the HIGH VOLTAGE toggle is in the OFF position and the 10-turn dial is turned all the way counter-clockwise and is reading 0.00. You can then remove the cover from the U-channel.

    c. Remove the cover of the U channel.

    d. Slide the laser assembly to the side (see figure).

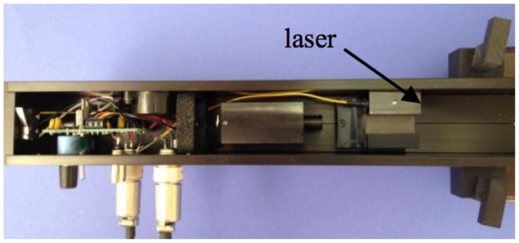
    

    Fig 6. Light source configured for bulb

    e. Turn the BULB POWER knob to half scale. ***Caution!*** The humble #387 flashlight bulb you're using will live longest if you minimize the time you spend with it dialed above 6 on its scale, and if you toggle its power switch only when the dial is set to low values.

    f. Turn the source switch to BULB, which should turn on the incandescence light bulb. To confirm the bulb is working, you'll need a dimly-lit room and a viewing card held just a few centimeters downstream from the bulb. You should see a dim and somewhat diffuse green spot on the paper.

    g. Replace the U channel cover and secure it with the four spring-loaded latches.

    h. Open the shutter (see Figure 1). Grasp and lift the shutter by pulling on the thick part of the shaft, not on the cable! This operation takes the photodiode out of the light path. The light passing through the detector-slit will now reach the sensitive area of the PMT.

2. Connect the output of the Photomultiplier to the input of the Pulse Counter with a BNC cable.

3. Use a digital multimeter to read the voltage applied to the photomultiplier tube. The voltage has been scaled by a factor of 1000! So a reading of 0.100 on the multimeter corresponds to a voltage of 100 V.

4. Optimize signal-to-noise levels
   a. Set the PMT high voltage setting to 900 volts (the voltmeter will read 0.9 V)
   b. PCIT Settings: GATE = AUTO GATE TIME = 0.1s DISCRIMINATOR THRESHOLD = 0.2 turns. Set to AUTO.
   c. Record three or four sets of counts with shutter open.
   d. Increase the DISCRIMINATOR THRESHOLD with shutter open until the count rate has dropped to approximately half. (At this setting dramatically fewer signals will be coming from noise.)
   e. Check the signal-to-noise ratio for this voltage-discriminator combination. Switch gate time to 10 s. Record a series of 2-3 counts open and 2-3 counts closed. Find the average signal-to-noise ratio.
5. If you need to open the U channel for any reason, confirm that the high-voltage 10-turn dial on the detector end of the apparatus is set to zero and that the high-voltage switch there is set to OFF. Also, to be sure the PMT is closed off from any possible light, check that the shutter is in the down position.

Part 7: Single-Photon Double-Slit Data Collection

We are finally ready to perform the double-slit experiment one photon at a time. Here's the procedure:

1. With both slits open, move the detector slit across several minima and maxima (at least 5 or 6) of the interference pattern and record the count rate vs. position x. You will want at least 6 or 7 points per interference fringe to resolve the fringes. Always change the micrometer in one direction only while taking data to remove any backlash effects. Have your lab partner type your data into a plotting program as you take the data so you can see the curve as you progress.

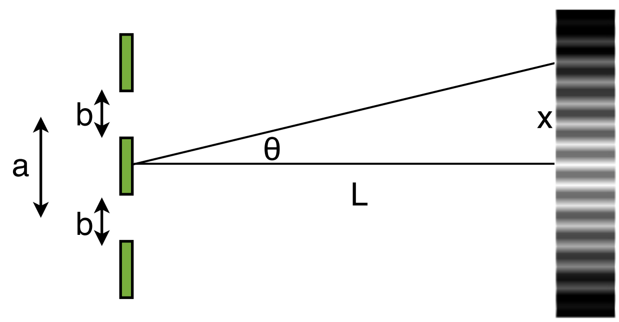
2. Repeat step 1 for the left slit open and the right slit open.

3. Measure the background level with both slits closed.

Part 8: Analysis

1. Plot your three data sets either on a single graph or on separate graphs (whichever you think is clearest). Make sure you first subtract the background count rate (measured with both slits blocked) from your data.

2. Plot the theoretical diffraction curves on the same graphs(s) as your data. You may choose either Fraunhofer Diffraction (far field approximation) or Fresnel Diffraction (near field). Below are the equations for Fraunhofer diffraction for single and double slits:



Single slit diffraction:

$$I_{\text{single}} = I_o \left(\frac{\sin\beta}{\beta}\right)^2 \quad \text{where } \beta = \frac{1}{2}kb\sin\theta \approx \frac{\pi b}{\lambda}\frac{x - x_0}{L}$$

where b is the slit width, I_0 is the beam intensity, L is the distance from the slit to the detector slit and x_0 is the center position of the diffraction pattern.

Double slit diffraction with equal beam intensities I_0 and slit widths b:

$$I_{\text{double}} = I_o \left(\frac{\sin\beta}{\beta}\right)^2 \cos^2\alpha \quad \text{where } \alpha = \frac{1}{2}ka\sin\theta \approx \frac{\pi a}{\lambda}\frac{x - x_0}{L}$$

The wavelength of the green light is approximately 550 nm, the widths of the slits *b* are about 0.1 mm and the slit separation *a* of 0.406 mm. Try adjusting these parameters along with x_0 to get a good fit to your data.

3. Estimate the count rate at the top of the central maximum when both slits are open. Now estimate the count rate at that position when the left and right slits are closed respectively. Given two beams of intensities I_1 and I_2 , the maximum intensity at the central peak with both slits open is $I_{\mathbf{max}} = I_1 + I_2 + 2\sqrt{I_1 I_2}$. How does your experimental value compare with this?

4. Assuming the PMT has a quantum efficiency of about 3%, estimate the maximum number of photons in the apparatus at a given time. Use this fact to argue that only a single photon passes through the slits at a time.

4. Summarize what evidence from this experiment suggests that light has a wave-like nature.

5. Summarize what evidence from this experiment suggests that light has a particle-like nature.

6. Define wave-particle duality. How does this experiment shed light (no pun intended) on wave-particle duality? Do you think this definition of duality satisfactorily describes the nature of light, or do you think the behavior of light remains paradoxical?