Double Slit Interference

Modern Physics Lab - Rochester Institute of Technology*

Introduction

Any text on quantum mechanics discusses the “wave-particle duality”. This experiment investigates the fundamental paradox, that is, that light behaves both as a wave, and as a particle.

In the first part of the experiment, a diode laser provides a fairly intense coherent light source, and the traditional Young’s double slit interference experiment allows the quantitative and systematic exploration of interference phenomena.

In the second part of the experiment, a very low light level source is used, with an extremely sensitive photomultiplier tube detection system. With this set up, light is of such low intensity that it arrives at the detectors as individual photons, one at a time. These particle-like quanta of light are observed as individual photon events, yet the light still demonstrates interference phenomena. This is the nature of the wave particle paradox: if light is going through the system one photon at a time, how can that photon “decide” which slit to go through in such a way that the number of photons going through each slit produce an “interference pattern”? What is an individual photon interfering with? How does the aggregate total of many such individual photons appear to be a wave? These questions (which one cannot answer) are the crux of the paradox.

Theory

Fraunhofer double slit theory predicts that the intensity of a double slit interference pattern is given by:

$$I(\theta) = I_0 (\cos\beta)^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \tag{1}$$

where

$$\alpha = \frac{\pi a}{\lambda}\sin\theta \tag{2}$$

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and

$$\beta = \frac{\pi d}{\lambda} \sin\theta \tag{3}$$

where a is the slit width for each slit, d is the spacing between slits, I_0 is the intensity at the center of the screen (θ=0), and θ is the angle away from this on-axis optical path.

In Equation 1, the maximum intensity is given by I_o, the first factor $(cos\beta)^2$ is the ideal double slit intensity (if the slits were each infinitesimally thin), and the final factor $(\frac{sin\alpha}{\alpha})^2$ is the effect of the finite slit width. You can see that the non-zero slit width provides a simple multiplicative modulation of the double slit intensity that you learned about in University Physics.

The single-slit diffraction equation (Eq. 4) can be obtained from Eq. 1 with removing the contribution from the double-slit interaction.

$$I(\theta) = I_0 \left(\frac{\sin\alpha}{\alpha}\right)^2 \tag{4}$$

Apparatus

Do not open the lid until you read this section!

The TeachSpin double-slit apparatus has an instruction manual that is available on My-Courses; consult this as needed.

The apparatus consists of three basic sections. On the left, there are two possible light sources, a red diode laser for strong illumination, and a low-light flashlight bulb with a green filter on it, for low-level illumination. These can be swapped in and out so either can be used to generate an interference pattern.

Through the middle there is a long optical channel, where various micrometer-adjustable slits are located (micrometer refers to the measurement tool, not that the scale is in μm) The slits will be discussed at length, below. Don't disturb them; it takes several hours to get them aligned.

To the right, there are detection electronics for two possible detectors. A photodiode is used to detect the relatively bright laser source. It converts optical intensity from the laser to a voltage. Alternatively, for low-light detection, a high sensitivity photomultiplier tube (PMT) is present. It detects individual photons and counts them.

The shutter which protects the PMT is a pull-up rod on the top of the right side of the apparatus. Besure it is pushed DOWN to close the shutter and protect the PMT. Also make sure the high voltage power to the PMT is turned off, on the electronics at the right end of the unit. If the shutter is closed and the high voltage is off, then you may open the lid.

The photomultiplier tube (PMT) wil be extensively damaged if it is exposed to room light or the laser.

The lid can be opened by pulling up the four latches and twisting; then the lid slides to the left, and lifts up.

If you hear an alarm on opening the optical cover, you must push the shutter closed IMMEDIATELY and evaluate what you have done incorrectly. Tell your instructor. The PMT may be damaged.

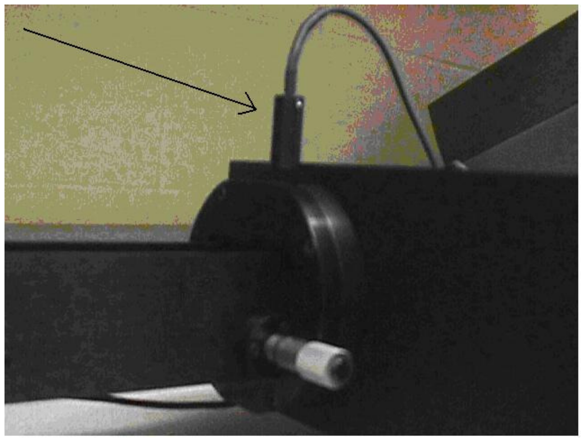

Figure 1: The shutter for the PMT is on top, at the right end of the optical channel. Push down to close.

At the left end are two distinct light sources, one a red laser and the other a green-filtered light bulb. The controls for the light sources are outside the optical channel at the left end. The power for the laser, or the light bulb, is on the left end of the unit, as shown in Figure 2

Figure 2: A toggle switch powers either the laser or the bulb. If the bulb is on, the intensity can be set with the knob control. For the laser, intensity is constant and is not impacted by the knob.

Moving from left to right, along the optical path, there are various slits. Some of the slits can be positioned with micrometers. Note that the slits are held in place only with small magnetic mounts; if you bump them they will become misaligned. The slits include:

1. Leftmost, an entrance slit, which is a narrow slit used to produce a coherent source of light.

2. Next, a double slit which is aligned and should not be disturbed.

3. Immediately to the right of the double slit, a wide "slit blocker", or slit mask, is mounted

on a micrometer drive. Positioning the slit blocker, with the micrometer, allows you to block the light from either one or both of the two slits in the double slit.

4. Finally, at the extreme right of the assembly, there is a detector slit. This very narrow slit can be positioned using its micrometer, and allows you to scan across the interference pattern, and pass only the light from that position into the detector.

For the laser source you can observe visually or use the photodiode as the detector. The photodiode output is at the right end of the unit; it is monitored iwth an ordinary DVM set to DC Volts. For the low light source (lightbulb with green filter) you will use the photomultiplier tube detector.

Week 1 Pre-lab

This Pre-Lab will have you modifying and playing with a Python script that plots the single- and double-slit patters. Make sure you plot the results and comment on what is happening.

1. For the following exercises, you can modify and use the python script provided, or write your own. The nominal slit widths and wavelengths are:

   $a = 0.085$ mm

   $d = 0.35$ mm

   $\lambda = 656$ nm for the laser

   $\lambda = 545$ nm for the light bulb with filter

   For the laser wavelength and the nominal slit sizes, plot the theoretical intensity patterns as a function of theta and both the single slit and double slit on the same graph. Distinguish the two by color and/or line style. Take $I_o = 1$.

   Make sure each plot is clearly labelled with the values of a, d and λ

2. Now hold d at the nominal value and vary a between 0.05 mm and 0.15 mm. Make at least 4 plots, in addition to the one you've already done at the nominal values, spanning this range.

3. Return a to its nominal value and vary d between 0.20 mm and 0.6 mm and plot I for the red laser (656 nm) .

4. Finally, go back to nominal values of a and d and plot I for both the red laser (656 nm) and the green lamp light (545 nm).

   Make sure to comment on what changing a and d actually does to your plots. What features of the pattern do they control?

5. Equation 1 assumes that both slits have the same intensity of light illuminating them, and that they have identical widths a. How would you expect the double-slit pattern

to change if the two slits had unequal illumination?

6. Is the central maximum intensity for the double-slit simply the sum of the maximum intensity for each of the two slits? If not, give an expression for the central maximum double-slit intensity in terms of the intensities from each of the two slits.

7. If you have time left continue onto the next section so you can become familiar with the equipment before next week.

Laser Illumination (week 1)

Visual Checks

Read through the Apparatus section. Make sure the PMT shutter is closed. Turn on the laser, open the lid. Sketch. Find and identify each slit.

Work through part of the Visual Observation part of the Laser Illumination lab; just tinker until you are sure you can find the central maximum peak, and you understand how the slit blocker and detector slits work.

With the lid open, turn the laser on and use one of the cards provided, or a slip of paper, to observe the laser spot near the left end (near the source). This laser is not dangerous unless you look straight at it, or receive reflctions from polished surfaces. Make sure the light bulb source is *down* and out of the way. Work your way down the optical channel, and observe the laser light after the various optical components.

Locate the larger-width slit, the "slit blocker", or slit mask, which is mounted on a micrometer. Observe the light just to the right of this; you may want the room lights off so you can really see the pattern. Adjust the slit-blocker position with the micrometer, starting from zero. As you adjust the slit blocker you can see

1. no light passing through

2. light from just the front slit,

3. light from both slits,

4. light from just the back slit,

5. all the way blocked and no light getting through.

Find all five of these optical arrangements with the slit blocker. Note the slit blocker micrometer reading for each. You have to be able to find these positions with the lid on for the rest of this experiment. When you are confident you understand the slit blocker, put it at the position that allows double slit interference. Please note that these micrometer readings may not "work" next time you use the apparatus if the slits have been bumped or moved the micrometer positions change.

It is likely that other students will leave the apparatus in an indeterminate state, that is different than when you last used it. It is important that you develop procedures to allow you to return the apparatus, notably the slit blocker, to a known state at the beginning of each lab.

The last slit you have to understand is the detector slit, at the extreme right end of the optical channel. Find it, and its micrometer. Put the lid on. Monitor the DVM attached to the photodiode. You can't put a card past this slit to just look at the light, you have to use the DVM and the photodiode. Scan the detector slit around, you should see fairly rapid oscillations of signal versus position of the detector slit. This is the double slit interference pattern that you will measure quantitatively in the next section.

Set the detector slit micrometer to the biggest photodiode voltage you can find; this should be the central maximum of the double slit interference pattern. If this is less than 0.7 V, find your instructor, something is misaligned. Feel free to open the lid as many times as needed to make sure you actually are running in double-slit mode, and that you are on the central maximum.

Verify that the photodiode is actually measuring the optical signal. Turn the laser off: does the photodiode voltage go to zero? If not, record the voltage observed for complete dark; this is an offset that should be subtracted from all photodiode readings.

Laser Illumination Data

Set the detector slit to the central maximum of the double slit interference pattern. Measure the intensity using the photodiode. Leave the detector slit set at that position, and move the slit blocker to block one slit, then the other slit. Thus you should have intensity measurements for front-slit only, both slits central maximum, back-slit only.

If the apparatus is aligned, the intensity for front-only should be roughly equal to the intensity for back-only. Is it? (Note, if they differ by a factor of two or more, find your instructor to realign the system.) Is the intensity for the double slit pattern's maximum simply the addition of the intensity for each of the two slits? What is it? Do intensities add, or how do they combine, for interfering waves?

Adjust the slit-blocker position for double slit interference. Adjust the detector slit for a *minimum* signal (destructive interference). Move the slit blocker so that instead of allowing light through both slits, it only allows light through one. Note the (increase) in signal at the detector. Think about this; you have just moved to half as much light going through the system (one slit instead of two) yet your signal at the detector increases! Why?

By varying the position of the detector slit, quantitatively measure

1. the single slit pattern from the back slit (slit blocker covers the front slit)
2. the double slit pattern
3. the single slit pattern from the front slit (slit blocker covers the back slit)

You will need to record intensity (photodiode output) versus position (detector micrometer reading) for each of these cases. In order to get an adequate plot of intensity versus position, you will need to move the detector slit in increments of approximately 5/100 mm using its micrometer for the double slit pattern, but you can use significantly larger steps for the single slit patterns. (Why?)

Week 1 Check in

Your raw data will be volts and position. Looking back at the pre-lab, the units of the x-axis of your plots should be angle (in radians) not position (in mm). Additionally, the maximum value of your plots should be 1, not whatever voltage you observed.

In your data, find the maximum intensity, as well as the center position (where the maximum intensity is). Normalize all intensities to the intensity at the center position. Normalzing data involves taking a data set and dividing every value in that set by the largest value found in the data. That way the data peaks at "1".

Now take your normalized data, and shift it so that the center of the curve is at $x = 0$ mm. Once this is done convert the position of the detector from mm to radians, using the fact that the path length from the slits to the detector is 500 mm.

Note: If your data contains a $\theta = 0$ data point you will not be able to fit it. This is because there is a divide by zero error in the Fraunhofer equation at $\theta = 0$. So either just delete this data point (you have so many it doesn't matter) or shift your curve so that your largest data point is not exactly at $\theta = 0$ (this is even likely, as you would have to get really lucky to measure the exact largest data point in the experiment).

Plot all three of your curves (the two single-slit, and the one double-slit) using the converted data.

Now try to fit one of the single-slit data sets to determine its width, a. You can use the known laser wavelength λ of 656 nm.

Week 1 Analysis

The laser wavelength λ is well known to be 656 nm. Using this as a known constant, determine a and d from your normalized intensity data using a fit.

Write a python script to fit the Fraunhofer normalized intensity function to all three of your data sets, with a and d as adjustable parameters (d is only needed for the dobule-slit data). Because this is not a linear fit you need to make sure to give Python intial guesses for any fit parameters. You can use nominal values found in the Pre-lab as a starting point.

If you are having issues getting the fit to work, plot a "theoretical" curve, and adjust a and d until it matches your data. Then use these values as the initial guesses for your fit.

Week 2: Low-Light Operation

Make sure the Photomultiplier Tube (PMT) shutter is closed and the high voltage stage is turned off

Once you are absolutely positive the PMT is off and shutter is closed, open up the light channel and put the light bulb source in, and the green filter, following the instructions in the TeachSpin equipment manual pages 9 and 10.

Verify that there is an oscilloscope attached to the PMT output, and a gated digital counter attached to the TTL pulse output of the PMT amplifier apparatus. In order to operate the gated counter, just press Reset on the counter to zero it, then press Start on the timer module to begin the gated time interval. The red light will turn on, on the timer, to indicate the gate is open and pulses are allowed through to the counter.

Make sure the lid is closed and latched before you turn on the PMT high voltage or open the shutter!

If now or in the future you hear an alarm on opening the optical bench cover, you must push the shutter closed and evaluate what you have done incorrectly before proceeding.

Follow the instructions page 10 and 11 of the TeachSpin manual until you have pulses. Do all this with the apparatus closed up, the shutter closed, and the light bulb turned a long ways down (1 or less on its dial). This is the "dark count" rate of the electronics. Take your time, this can be tricky. Turn up the high voltage to the PMT until you see pulses, this should happen at about 400 to 500 V (4 to 5 on the ten-turn knob).

If you are uncertain if you are getting pulses hook up the oscilloscope to the PMT outputs at the right end of the apparatus and try to see if there are any pulses (as directed in the manual).

Once you have dark-count pulses and you think you know how to run the electronics, proceed to actually measure photon events one at a time, as follows.

Keep the lid shut at all times !!!

- Set the slit blocker so that both slits are illuminated, using the positions or procedures you determined last week. Note that the positions may have changed if the slits have been realigned. You'll have to figure out a procedure to make sure you are in a double slit pattern, **WITHOUT OPENING THE LID**.
- Set the light bulb to a setting of about half power, which should give you a low light level.
- Measure the dark count rate (shutter closed) for a few one second intervals. You should be getting a few counts, not many tens of thousands, in a one second time interval, with the PMT bias set at a voltage that gives you counts.

- Now, finally, open the shutter. Your count rate should be a great deal higher.
- Adjust the detector slit to the central maximum peak of the double slit pattern. You should know where this is from last week, or how to find it, again **WITHOUT OPENING THE LID**
- Verify the detector slit position by counting for a few positions on either side - this is a rough measurement. Once you are roughly on top of the peak, you are ready.

You have the PMT counting real optical photon pulses, and the detector slit is on the central maximum.

Week 2 Pre-lab: PMT response and counting statistics

PMT response measurement

Set up the optics so you are on the bright central maximum of the double slit pattern.

It is important to determine an optimum bias setting (voltage applied) to the PMT. In order to do this, measure the count rate for 1 second intervals for PMT biases of 400 to 600 V (lower voltages than this give zero counts). Measure the count rate for the shutter open (Light Count Rate- L), and the shutter closed (Dark Count Rate - D). Note that the dial setting is roughly, but not exactly, 1/100 of the actual voltage applied. We are not concerned with absolute voltage, so it's ok to think in "dial setting". Leave the optics alone during these measurements. You are checking the response of the PMT as a function of its bias, for a constant light level.

What we are looking for is the maximum signal to noise ratio. You cannot just pick the place with the largest light count as that also has a large dark count, as the dark count grows faster as you increase the bias voltage. The signal to noise ratio is calculated as (L-D)/D. We use the (L-D) for the numerator since this is the actual signal above the baseline noise (the light counts minus the dark counts). Plot this as a function of voltage, and the peak is where we have the highest signal to noise ratio.

All PMT's need this calibration run done before use, in order to determine an ideal bias voltage. One's temptation is to use too high a bias, which increases the dark count (noise) needlessly.

Counting Statistics

The statistical scatter in counting discrete events depends on the number of counts. Specifically, the uncertainty σ_{n-1} is exactly equal to $\sqrt{N}$, where N is the average number of counts. For more information on this see for example:

`http://people.ccmr.cornell.edu/~muchomas/8.04/Lecs/lec_statistics/node18.html`

or any text on probability. This is why it is always better to count long enough to get "a lot" of counts: even though the standard deviation is going up like $\sqrt{N}$, the fractional error $\sqrt{N}/N$ decreases.

- Leave the optics at the central maximum of the double slit pattern. Set the PMT bias to a good value based on your results above. Set the timer apparatus to measure for 1 second time intervals.
- Measure the Light Count rate ten times each, for bulb intensity settings from 2 to 8. Record each of these repeated measurements.
- Increase the timer to 4 second intervals.
- Again measure the Light Count rate ten times each for bulb intensity settings from 2 to 8. Record each of these repeated measurements.
- Compute the standard deviation σ_{n-1} and the average number of counts N for each of the ten repeat measurements. Any inexpensive scientific calculator can do this, as can Excel (STDEV function).
- Combine all the data and plot standard deviation σ_{n-1} versus average counts N. From the slope, find the power law. (Hint; remember, statistics tells us that σ_{n-1} is strictly equal to $\sqrt{N}$, so you had better get a power law of about 1/2.)
- At what average number of counts does the strictly statistical scatter in the data fall below 2%? 1%? Does this depend on our apparatus, or optics, or PMT?

Wave-Like Interference of Single Photons

With the PMT bias set at a good place (as determined above) and with bulb and timing settings that produce a good counting rate (a few thousand per second on the central maximum), take a set of data of counts versus position, by moving the detector slit. This should be exactly the same procedure as you used with the laser and photodiode, except now you are using the PMT and counter along with the dim green light source.

You will still need to take the data every 5/100 mm for the low-light setup. It is not neccesary to take the single slit data again as what we are interested in here is the interference of two individual photons.

Analysis: Low-Light Data

Plot your low-light double-slit data.

Now fit the low-light data to determine the wavelegnth of the filtered lightbulb. You can use the values of a and d that you determined with your laser data as constants, so there is no need to fid them. What wavelength do you measure? Is it what you expect from looking at the bulb (with filter)?

Next you will demonstrate the wave-like interference of single photons.

1. Compute the "time of flight" for a photon from the double slit to the detector. You know both the speed of the particle and how far it is traveling so this should be simple.
2. Next, compute the time between photons from your count rate at the maximum signal. This is the reciprocal of your maximum count rate per second.
3. Then compute the fraction of time that there is at least one photon in flight within the apparatus.
4. If there is only one photon at a time in the apparatus, then what is "interfering" with what?