

Single- and Double-Slit Interference

Goals:

- To see the interference pattern produced by coherent light passing through single- and double-slit apertures.
- To explore how these patterns depend upon the size or separation of the apertures.
- To use the interference pattern and a known slit size/separation to accurately determine the wavelength of a coherent light source.

Equipment:

- Optical bench
- Laser diode w/ power supply
- Linear translator
- Aperture bracket for light sensor
- Single Slit Set
- Multiple Slit Set
- PASCO Xplorer (or Xplorer GLX)
- PASPORT Light Sensor w/ cable
- PASPORT Rotary Motion Sensor
- Meter stick

Introduction:

Nowhere is the wave nature of light demonstrated more clearly than in the phenomenon of interference. Many kinds of waves exhibit interference: light waves, sound waves, water waves, and so on. The underlying physics is relatively simple: when several different waves arrive at the same point in space at the same time, they pass right through each other. But at the point where the waves overlap, the total wave strength there is just the sum of the individual waves' strengths at that point. We say that these waves obey the **superposition principle**.

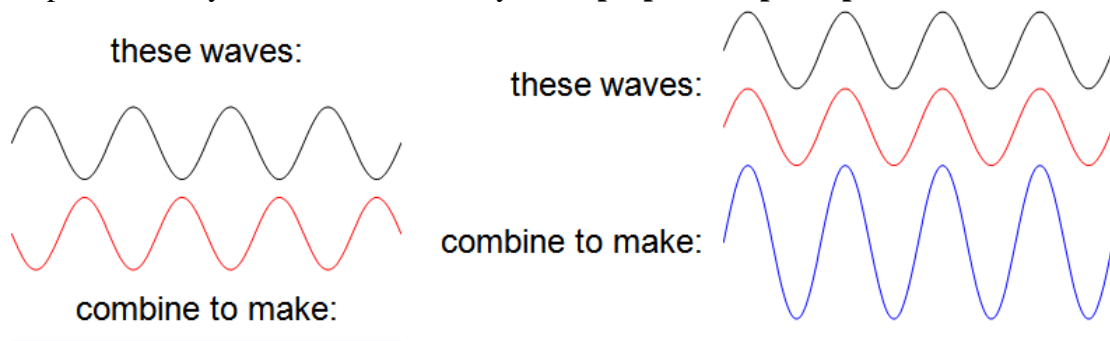


Figure 1 Superposition of equal-amplitude, equal-frequency waves. In (a), the two waves are in phase, and the result is constructive interference. In (b), the two waves are 180° out of phase, resulting in destructive interference.

If we restrict our attention to just two waves at a time, and make the assumptions that these waves have the same amplitude and frequency, then we can see two limiting cases of interest to us. When the waves are **in phase**, or in other words, when the oscillations of the waves match up

exactly, we can see that the waves will **constructively interfere**, and the net wave amplitude will be doubled, as shown in Figure (a). If, at the other extreme, the two waves are exactly **180° out of phase**, the waves will **destructively interfere**. In this case, the net wave amplitude is zero, meaning that the waves have perfectly “canceled” each other out, as shown in Figure (b).

One way in which waves can drift out of phase with respect to each other is if they travel different distances to arrive at the same point. As a specific example, we observe that when **monochromatic, coherent** light passes through a narrow aperture (where “narrow” in this context implies that the width of the opening is comparable to the wavelength of the light), it spreads out into the region which we would classify as the “shadow” of the slit. (The shadow is the region behind the slit that light would not reach if it traveled perfectly straight lines.) The spreading of light after passing through an aperture such as this is known as **diffraction**. A top-down cartoon of this phenomenon is depicted in Figure 2 below.

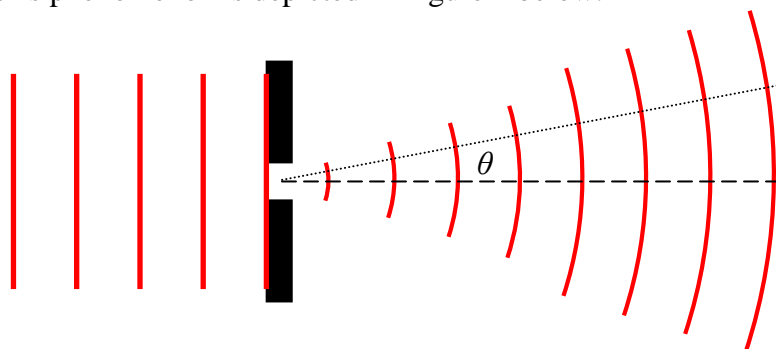


Figure 2 The spreading of a wave as it passes through an aperture whose width is comparable to the wavelength of the wave is known as **diffraction**. The pattern will be most intense along the forward direction (represented as a dashed line.) We will be interested in how the intensity varies as we look at various angles θ away from the center.

As the light passes through each point of the opening, it spreads out in all directions, interfering, in some sense, with itself. In our minds, we imagine that each point in the opening is a new source of a “wavelet” of light. Due to their slightly different starting positions, each of these wavelets will travel minutely different distances to arrive at the same point in space. This will introduce a phase difference in the multitude of waves arriving at that location. Where the waves are generally all arriving out of phase with each other, the net wave amplitude will approach zero. Where the waves are generally arriving in phase, we expect the net wave amplitude to be large. With only a single slit, though, only points directly in front of the opening along the direction of propagation will generally arrive all in phase, so we expect to see a bright central spot, surrounded by fainter, alternating bands of bright and dark areas, where constructive and destructive interference occur, respectively.

Most wave sensors (*e.g.*, in humans, our “sound sensors” are our ears, which receive sound waves, and our eyes act as light sensors, receiving light waves) are sensitive to the *intensity* of the wave, rather than the amplitude. For most types of waves, the intensity is related to the *square* of the wave signal. In the present context of light waves, we relate intensity with brightness — the brighter a light source is, the higher its intensity. (For sound waves, we would say that the louder a sound is, the higher its intensity.) From the discussion above, we see that light passing through a single slit will create an alternating pattern of bright and dark areas, which we could equivalently describe as an alternating pattern of high and low intensity. We will

often choose to visualize an interference pattern by showing its intensity as a function of position, for instance, of a diffraction pattern shining on a screen, as is shown in Figure 3.

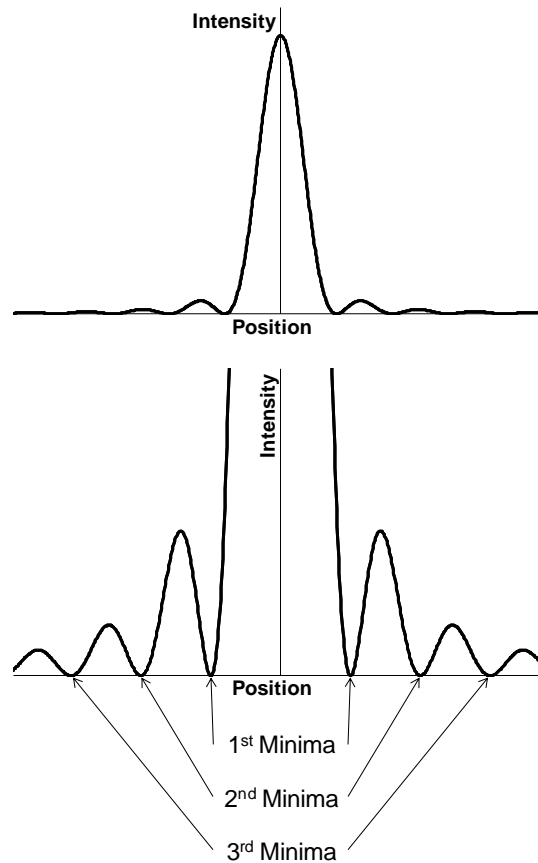


Figure 3 Intensity versus linear position of a single-slit diffraction pattern. The single-slit pattern will consist of a large, central bright spot, flanked symmetrically by alternating dark and bright areas. The central maximum will be at least ten times brighter than any of the side maxima. *Inset:* A zoomed-in display of the side maxima and minima. We count the minima outward from the central maximum, symmetric across the center.

In the single slit pattern, the angular position of the maxima cannot be described via a simple trigonometric expression, but the minima (dark spots) can. We find that the single-slit *minima* will be located at an angle θ away from the central maximum where θ must satisfy

$$a \sin \theta = p\lambda \quad p = 1, 2, 3, \dots, \quad (\text{Eq. 1})$$

with a representing the slit width, λ the wavelength of the light, and where p is an integer which labels the minima, counting outward from the center as depicted in Figure 3. In general, angles are more difficult to measure than distances, and so we will often not attempt to ascertain the *angular* position of the minima directly, but will rather focus on their *linear* position, at some constant distance L away from the slit. This arrangement is typically shown in a top-down view, as is shown in Figure 4. From that figure, we can see how to relate the linear distance y of a maximum or minimum relative to the central maximum and the angle θ that the maximum or minimum makes with respect to the central maximum. Using trigonometry, we can see that they are related by

$$y = L \tan \theta . \quad (\text{Eq. 2})$$

By using both Equations 1 and 2, we can use the linear position of the intensity minima produced by a single slit of known width a in order to determine the wavelength of the light used in this experiment.

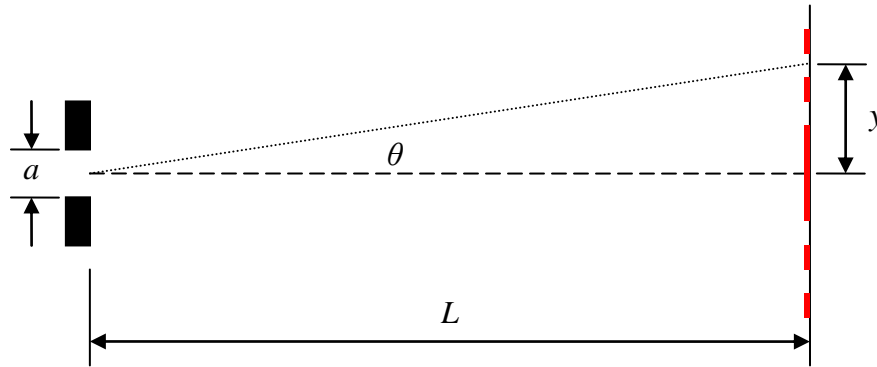


Figure 4 Measuring the linear position of the 2nd-order minimum to the left of the central maximum. The interference pattern produced by the single slit is allowed to shine on a screen (or piece of paper) a uniform distance L away from the slit. We can then measure the linear location of the minima, and using trigonometry, determine at which angles, with respect to the central maximum, these minima are located.

In the second portion of today’s experiment, we will also explore the interference pattern produced by two slits, often known as **Young’s double-slit experiment**, in honor of Thomas Young who performed this experiment in the early 19th century. We will illuminate two narrow slits with the same monochromatic, coherent light source as before, but we now expect to see a different pattern. First of all, more light is now going to reach our screen, and so we expect the overall pattern to be brighter (more intense). But more interestingly, we now expect to see an interference pattern due to the fact that the light from the two slits will travel different distances to arrive at the same point on the screen. If we consider two very narrow slits separated by a small distance d , the diffraction of the light from each slit will cause the light to spread out essentially uniformly over a broad central region and we would see a pattern such as the one depicted in Figure 5.

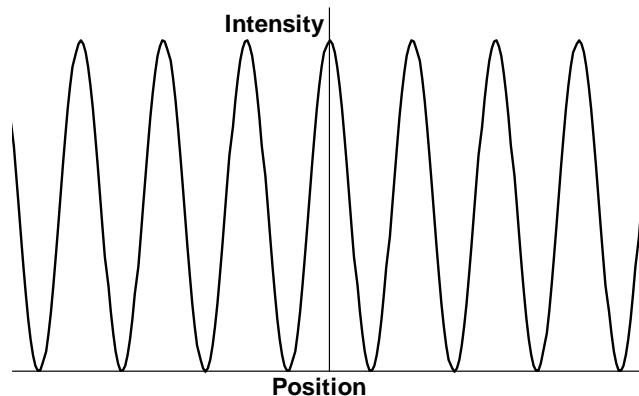


Figure 5 Idealized double-slit intensity pattern as a function of position. This is the pattern we would see if the size of the individual slits is relatively small.

If the individual slits are somewhat larger, so that the diffraction patterns are not so spread out, we would expect to see a somewhat more complicated pattern, which shows both the diffraction pattern and double-slit interference pattern simultaneously, as depicted in Figure 6. In both cases, the maxima and minima will appear where the conditions for constructive and destructive interference are satisfied, respectively.

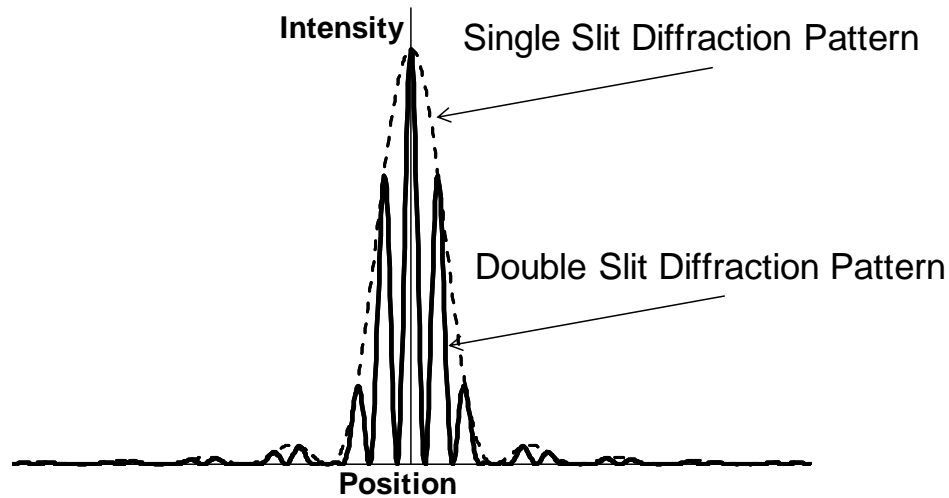


Figure 6 Actual (non-ideal) double-slit interference pattern. The maxima and minima appear where constructive and destructive interference occur, respectively, due to the path length difference between the waves propagating from each slit to the observation point (screen). This pattern is attenuated by the single-slit “envelope”. You can envision this pattern being created by multiplying the patterns in Figure 3 and Figure 5 together at each point along the axis.

For the double-slit interference pattern, intensity *maxima* will be located at an angle θ relative to the central maximum, where θ will obey the relation

$$d \sin \theta = m\lambda \quad m = 0, 1, 2, 3, \dots \quad (\text{Eq. 3})$$

The intensity *minima*, on the other hand, due to the double-slit interference will occur at an angle θ relative to the central maximum given by

$$d \sin \theta = (m + \frac{1}{2})\lambda \quad m = 0, 1, 2, 3, \dots \quad (\text{Eq. 4})$$

Please note that Eq. 1, which describes the necessary condition for *minima* to appear in a single-slit diffraction pattern, looks qualitatively the same as Eq. 3 which describes the necessary condition for *maxima* to appear in the double-slit interference pattern. They describe very different scenarios, and you should make every effort to keep them distinct in your mind.

Name: _____

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Directions:

In this experiment, a laser diode will produce a continuous, coherent light source, which will shine through a small aperture, or slit. At the opposite end of the optical bench, a light sensor is set up that will measure the brightness (intensity) of the light shining onto that point in space. By moving the light sensor back and forth, we can see how the light intensity varies with position.

Note: Do not stare directly at the laser or point the laser toward anyone else's eyes.

Activity 1: Single-slit diffraction

1. Set up the laser diode at one end of the optical bench and turn it on.
2. Place the Single-Slit Set (in its mount) on the optical bench in front of the laser source (approximately 3 cm in front of the laser). Rotate the disk on the Single-Slit Set until laser light shines through the 0.04-mm slit. Rotate the black lens holder until the diffraction pattern produced by the slit is horizontal.
3. Adjust the alignment of the laser diode with the two thumbscrews on the back of the laser. You should adjust the vertical and horizontal alignment so that the laser beam is roughly centered on the slit in the Single-Slit Set.
4. Verify that the cable from the Light Sensor is plugged into Input 1 on your Xplorer GLX (the top-left port) and that the cable from the Rotary Motion Sensor is plugged into Input 2 (the top-right port).
5. Prepare your GLX to take data:
 - a. Press the power button on the Xplorer GLX to turn it on.
 - b. Press the home button (⏠) to return to the main menu.
 - c. Navigate using the arrow keys, and highlight the 'Data Files' icon. Select the 'Data Files' item by pressing the checkmark button (✓).
 - d. Open the setup file:
 - i. Arrow up to select the folders pane.
 - ii. Arrow right to select the 'Flash' folder.
 - iii. Arrow down and highlight the '251_Interference' file.
 - iv. Press F1 (F1) to Open the file.
 - e. Press the home button (⏠) to return to the main menu.
 - f. Highlight the 'Graph' icon and select it using the checkmark button (✓). You should see a graph that is configured to display the measured light intensity plotted versus the linear position of the light sensor.







6. On the Light Sensor, there are three buttons, each with an icon next to it representing the three sensitivity settings of the sensor. Press the button with the 'candle' icon to set the sensor to its highest sensitivity.
7. If it is not already set, turn the aperture bracket immediately in front of the Light Sensor to position #3.
8. Using the measuring tape on the optics bench or the meter stick, measure the distance between the single slit and the light sensor. Record this below.

Distance between slit and sensor, L : _____

You are now ready to take intensity measurements. You will push the light sensor on its track through the interference pattern created by the laser light shining on the slit, while the GLX records the position and intensity data. *Do your best to push the light sensor **slowly** and **steadily** to achieve the best results.* You may wish to practice pushing the apparatus back and forth several times to become accustomed to it.

9. Ask your Teaching Assistant to turn off the lights in the room. Hold a sheet of white paper in front of the light sensor so that you can see the entire diffraction pattern.

Q1. Sketch below the interference pattern you see on the sheet of paper.

10. Slide the light sensor far from the brightest spot of the diffraction pattern. Press the play button  on your GLX to begin recording data, and then *slowly* move the Light Sensor through the pattern. Again, you should move the sensor slowly, steadily, and in only one direction. Be sure to stop the recording of data (press  again) when you have completed a sweep. Press F1  to auto-scale the graph.
11. Even though you've auto-scaled the display, you'll likely need to do some fine-tuning to achieve the most useful display of the data:
 - a. Press F2  once to enter 'Scale' mode. You can press the up arrow to increase the resolution on the vertical axis and the down arrow to decrease the resolution. Similarly, the right and left arrow keys can be used to increase or decrease the resolution on the horizontal axis, respectively.
 - b. Press F2  again to enter 'Move' mode. Now, pressing up, down, left or right will move the axes of the graph in that direction.
 - c. You can get out of either Scale mode or Move mode by pressing Escape .

12. Using the techniques described above, scale and move your graph so that the most interesting portions of the diffraction pattern are clearly displayed within the boundaries of your graph window. (Long, flat portions of the graph where the intensity was essentially constant are not very interesting.) Your graph should qualitatively match the single-slit diffraction pattern shown in the introduction (*cf.* Figure 3). If your graph is very rough and you cannot make out maxima and minima, re-take the data.
13. Once you have a relatively clear graph on which you can see the minima and maxima of the single-slit diffraction pattern, we'll want to know the position of the minima so that we can determine the wavelength of the laser light. Use the data cursor and the arrow keys to locate the linear position of the various minima. Record them in the table below.

Order	Location of Intensity Minima		
	Left of Central Max.	Right of Central Max.	Average: $\frac{1}{2}(x_R - x_L)$
$p = 1$			
$p = 2$			
$p = 3$			

14. In the table above, calculate the *average* linear distance of the minima from the central slit by calculating half of the difference between the location of the minima on the right side of the central maximum and the location of the minima on the left side of the central maximum.
15. Use these distances, your knowledge of the slit width a , and the distance between the slit and the sensor L to compute the wavelength of the laser light (in nanometers).

Order	Computed Wavelength
$p = 1$	
$p = 2$	
$p = 3$	
Average	

Q2. Does your average value for the wavelength seem reasonable? What criteria are you using to determine whether or not the wavelength seems reasonable?

16. Print your graph:
- a. If necessary, re-scale and move your graph to display the full intensity pattern within the available graph window.
 - b. Carefully unplug the light sensor cable, rotary motion sensor cable, and power cable from your GLX. Take your Xplorer GLX to one of the available printers, and connect the provided USB cable to the available port on the right side of the GLX.
 - c. Press F4 (F4) to access the 'Graphs' pull-down menu.
 - d. Arrow down to highlight 'Print' and select it with the checkmark button (✓).
 - e. Press F1 (F1) to begin printing. Include this graph with your lab report.
17. When printing is complete, return the GLX to your work area, plug the light sensor into sensor port 1 (top-left), the rotary motion sensor into port 2 (top-right), and plug in the power cord.
18. Now, turn the Single Slit Set to the 'Variable Slit' aperture. This is a slit that varies in width as you turn the dial of the slit set. Determine in which direction the slit becomes wider.
19. While holding a sheet of paper in front of the light sensor, turn the disc of the slit set from the smallest slit to the largest slit and observe how the diffraction pattern changes.

Q3. Describe what happens to the diffraction pattern as the aperture becomes larger and larger.

Q4. Based on your observations, how would the diffraction pattern be affected if the slit opening were made to be much, much larger?

Activity 2: Double-slit diffraction

20. Set up Multiple-Slit Set (in its mount) on the optical bench approximately 3 cm in front of the laser. Rotate the disk on the Multiple-Slit Set until laser light shines through the double-slit with the 0.04-mm slit width and 0.25-mm slit separation.
 21. Hold a sheet of white paper in front of the light sensor so that you can see the entire interference pattern.
- Q5.** Sketch below the interference pattern you see on the sheet of paper.

22. Slide the light sensor far from the brightest spot of the interference pattern. Record data (begin by pressing \blacktriangleright) while you *slowly* move the Light Sensor through the pattern. Again, you should move the sensor slowly, steadily, and in only one direction. Be sure to stop the recording of data (press \blacktriangleright) when you have completed a sweep. Press F1 F1 to auto-scale the graph.
23. Examine your graph (by scaling and moving your graph as necessary) to see if it clearly represents the same information you sketched in **Q5** above. Your graph should qualitatively match the double-slit interference pattern shown in the introduction (*cf.* Figure 6). If your graph is very rough and you cannot make out maxima and minima, re-take the data.
24. Now rotate the Multiple-Slit disc so that the laser light shines through the slits marked “Multiple Slit (2)”. This is a pair of slits, each of width $a = 0.04$ mm, separated by a distance $d = 0.125$ mm.
25. Again record data (begin by pressing \blacktriangleright) while you *slowly* move the Light Sensor through this interference pattern, moving the sensor steadily through the pattern, and in only one direction. Be sure to stop the recording of data (press \blacktriangleright) when you have completed a sweep, and press F1 F1 to auto-scale the graph.
26. You should have two clean data runs (perhaps out of a set of several runs) representing your best efforts at capturing the intensity data, for the $d = 0.25$ mm case and for the $d = 0.125$ mm case. Print and submit both of these graphs with your lab report by following these steps:
 - a. To select a specific data run from the ‘Graph’ display, press the checkmark button \checkmark and arrow right to highlight the “Run #N” field. Press the \checkmark button again to access a pull-down menu of all the data runs you’ve taken. Arrow up or down to highlight the run you wish to print and then press the \checkmark button again to display that data.

- b. As necessary, re-scale and move your graph to display the full intensity pattern within the available graph window.
- c. Carefully unplug the light sensor cable, rotary motion sensor cable, and power cable from your GLX. Take your Xplorer GLX to one of the available printers, and connect the provided USB cable to the available port on the right side of the GLX.
- d. Press F4 (F4) to access the 'Graphs' pull-down menu.
- e. Arrow down to highlight 'Print' and select it with the checkmark button (✓).
- f. Press F1 (F1) to begin printing.
- g. Now select the other data run requested, and repeat steps b–g to print it.
- h. Be sure to label the two printed graphs to indicate which one corresponds to the 0.25-mm case and which to the 0.125-mm case.

27. When printing is complete, return the GLX to your work area, plug the light sensor into sensor port 1 (top-left), the rotary motion sensor into port 2 (top-right), and plug in the power cord.

Analysis

Q6. Describe all the differences you've observed between the two double-slit interference patterns (*e.g.* was one noticeably brighter than the other, did one have more interference peaks than the other, was one broader than the other, etc.)

Q7. How does the intensity of the brightest spots in the double-slit patterns compare to the intensity of the brightest spot in the single-slit pattern (from your print-outs)? Offer an explanation as to why this might be the case.

Q8. Based on your two graphs, what would you expect to see if you looked at an interference pattern created by two slits, each of width $a = 0.04$ mm, but separated by $d = 0.50$ mm?

Q9. Turn the dial on the Multiple-Slit set to the $a = 0.04$ mm, $d = 0.50$ mm, and observe the pattern produced on a sheet of paper. How does the actual pattern compare to your expectations above? Turn off the laser diode when you're done answering this question.

Q10. Describe a method by which you could again determine the wavelength of the laser light, but now by using the double-slit interference patterns you collected. (Be specific about what you would measure, what you'd calculate, and how this gives you the wavelength of the light.)
