

## *Experiment 9*

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# **Diffraction and Interference**

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### **9.1 Objectives**

- Observe Fraunhofer diffraction and interference from a single-slit and a double-slit.
- Calculate the slit width, which produces the single-slit diffraction pattern, and observe how the slit width affects the diffraction pattern.
- Verify Babinet's Principle by observing the diffraction pattern from a thin wire.
- Calculate the slit width and the slit spacing for the double-slit from the interference pattern produced by light passing through it.

### **9.2 Introduction**

The nature of light has been investigated for millenia. There have been various theories about light, including such ideas as light being emitted from our eyes to see things to it being one of the five elements. Eventually, the question was boiled down to two competing theories: is light a particle or a wave? While we know now that it can act as either a particle or a wave, depending on how you measure it, the diffraction and interference of light is clear evidence for its wave nature. Today you'll experience the evidence that supports light as a wave.

## 9.3 Key Concepts

As always, you can find a summary online at HyperPhysics<sup>1</sup>. Look for keywords: interference, diffraction, double-slit

There are many simulations of diffraction and interference on the web. Here are some favorites:

- <http://ngsir.netfirms.com/englishhtm/Diffraction.htm>. Single-slit diffraction. You can adjust the wavelength and slit width.
- <http://ngsir.netfirms.com/englishhtm/Interference.htm>. Double-slit diffraction.
- <http://www.falstad.com/ripple/>. Comprehensive “ripple tank” simulation. You can select which configuration you want from the top menu on the right, including single and double slits, as well as more complicated wave phenomena.

## 9.4 Theory

### Wave behavior around barriers and through slits

All of the phenomena studied in this lab result from the same physical consequence of wave interference. Recall that when two waves encounter one another they “interfere” either destructively (they subtract) or constructively (they add). In this lab we will force light of a single wavelength (from a laser) to pass through slits, or around obstructions, near the laser and shine on a screen more than a meter away. Because the slits are of finite size, different light “rays” or waves come from slightly different places near the slits and travel slightly different path lengths to get to the screen. Depending on these different path lengths, the waves might arrive: 1) in phase, 2) a bit out of phase, or 3) totally out of phase which results in bright, dim, or no light, respectively.

Constructive interference takes place at locations where two waves are in phase (for example, both waves have a crest). Destructive interference takes place where two waves are out of phase (for example, one wave has a crest, the other has a trough). Each circumstance can result from light

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<sup>1</sup><http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html>

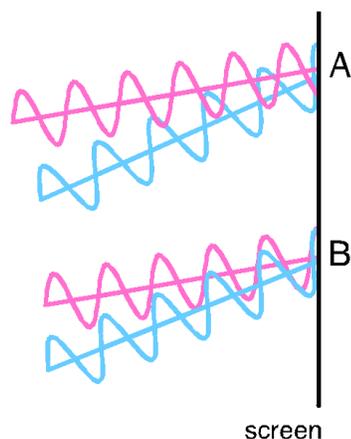


Figure 9.1: Two waves (one pink and one blue) impinging on a screen from a slit arrangement (unseen from the left). The top picture shows 2 waves out of phase with each other and combining destructively at point A. The bottom pictures shows 2 waves in phase with each other and combining constructively at point B.

emerging from either two different slits or two different spots within a single slit. The two extremes are shown in Fig. 9.1. At point A on the screen the two light rays arrive out of phase (the pink wave is at a trough while the blue wave is at a crest) and experience destructive interference so the screen will be dark. At point B, the two rays arrive in phase (both the pink and blue waves are at a crest) and experience constructive interference so the screen will be bright.

There are two phenomena of light acting like a wave that will be explored in today's lab. The first is called **diffraction** and occurs when light passes by a single obstruction or through a tiny opening, called a "slit". The second is called **interference** and occurs when light passes through multiple slits. Notice that both these phenomena are really effects of interference, but we reserve the word "diffraction" for single-slit (or single-obstruction) phenomena and use the word "interference" for phenomena that involve multiple slits (or obstructions). Today you will be looking at patterns formed on a screen after shining light through a single-slit or a double-slit. Since a double-slit is made up of 2 single slits you may have already guessed that

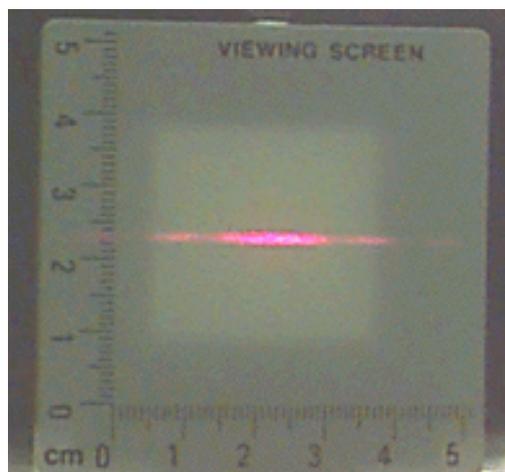


Figure 9.2: Diffraction pattern produced by laser light passing through a single slit.

the double-slit pattern will have components coming from both interference and diffraction.

### Diffraction from a single slit

Fig. 9.2 is a photograph of a single-slit diffraction pattern. In this lab, you will see light and dark places on the screen that correspond to constructive and destructive interference when light waves pass through a single-slit. Notice that the pattern has a wide, central bright spot and then repeating spots on each side which are less bright and narrower. A plot of the intensity (brightness) of the light is shown in Fig. 9.3. (The units are arbitrary, but all of the same scale.)

For a diffraction minimum (a dark spot) to occur, the waves must be out of phase and their **path length difference** must be an odd-integer-wavelength. This gives rise to the condition that:

$$a \sin \theta_n = n\lambda. \quad (9.1)$$

where  $a$  is the slit width,  $n$  is the order number of the diffraction minimum (dark spot),  $\theta_n$  is the angle from the center line to the  $n$ th diffraction minimum and  $\lambda$  is the wavelength of light. Fig. 9.4 shows a diagram of

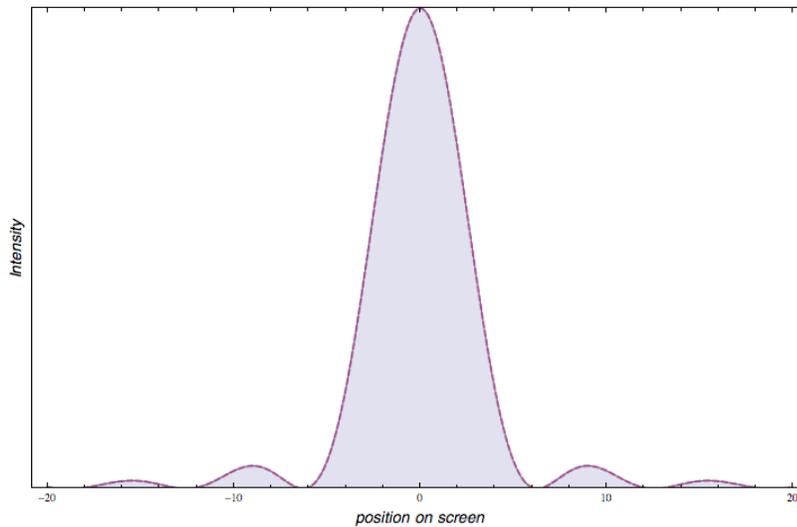


Figure 9.3: A plot of the intensity of light from diffraction through a single-slit as a function of position on the screen.

the single-slit setup and labels relevant variables. In the upper diagram the laser light is coming from the left, shining on a single slit of width  $a$  and then traveling a distance  $D$  to the screen. The trig relation  $\tan \theta_n = \frac{x_n}{D}$  can be used to replace the angle  $\theta_n$  in Eq. 9.1 with the distance  $D$  between the slit and the screen and the distance  $x_n$  between the central (or principal) maximum and the  $n$ th diffraction minimum (dark spot) giving:

$$\sin \theta_n = \sin \left[ \arctan \left( \frac{x_n}{D} \right) \right]. \quad (9.2)$$

The lower diagram in Fig. 9.4 shows the intensity distribution from the single-slit with examples of the variables  $n$  and  $x_n$  labeled. Combining Eqs. 9.1 and 9.2 gives the **Diffraction Equation**:

$$a = \frac{n\lambda}{\sin \left[ \arctan \left( \frac{x_n}{D} \right) \right]}. \quad (9.3)$$

There are a few things to note about Eq. 9.3. The variable  $n$  is called the “order” number and relates to the position of the minima (dark spot) in the diffraction pattern. If  $n = 1$  that is the “first” order dark spot to the

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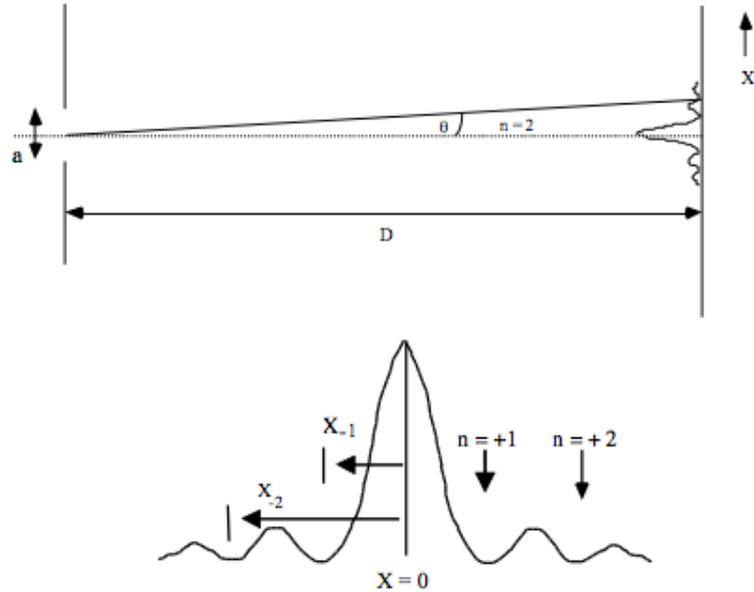


Figure 9.4: Geometry and intensity distribution in single-slit diffraction. The diagrams are labeled with the variables used in the diffraction equation.

right of the central maximum (bright spot). If  $n = -2$  that is the “second” order dark spot to the left of the central maximum. Notice that  $n$  can be positive or negative indicating to which side of the central maximum you are referring. Often times you are given the order of the minima stated as “fourth order” which tells you that  $n = 4$ . Also notice that  $x_n$  is a signed distance: it is positive for positive  $n$  (to the right of  $x = 0$ ), and negative for negative  $n$  (to the left of  $x = 0$ ). When measuring  $x_n$  for this lab make sure to measure your distance from the center of the principal maximum ( $x = 0$ ) to the center of the  $n$ th dark spot.

Generally, when looking at the diffraction pattern from a single-slit the distance  $x_n$  is much, much smaller than  $D$  ( $x_n \ll D$ ). In this case  $\theta_n$  is very small and the **small angle approximation** can be used, which states that  $\sin \theta_n \approx \tan \theta_n \approx \theta_n$ . Using the small angle approximation reduces Eq. 9.3 to:

$$a = \frac{n\lambda D}{x_n}. \quad (9.4)$$

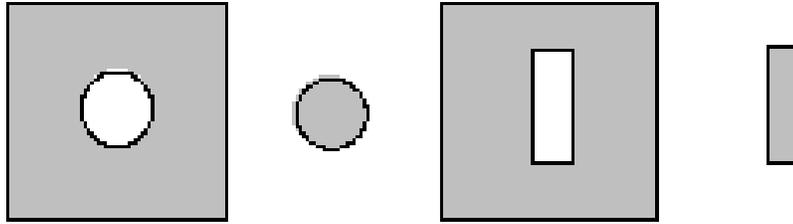


Figure 9.5: Examples of complementary screens. The gray regions are opaque and the white regions are transparent.

where  $a$  is the slit width and  $x_n$  is the distance between the central maximum and the  $n$ th diffraction minimum.

### Babinet's principle

Two screens are said to be **complementary** when the transparent regions on one exactly correspond to the opaque regions on the other and vice versa. Fig. 9.5 shows two examples of complementary screens. Babinet's Principle implies that the Fraunhofer diffraction patterns from complementary screens are nearly identical. Thus, if a thin wire were placed in the laser beam, one would expect to obtain a diffraction pattern similar to that of a single-slit.

### Interference and diffraction from two slits

Now let's add a second slit, called a double-slit, and see what happens to the pattern on the screen. You might think that adding another slit would add more light but the photo in Fig. 9.6 shows what actually happens. Compare this photo to the one for a single-slit in Fig. 9.2. There is still a wide, central bright spot but it now has several dark spots inside it. **Adding more light by opening a second slit leads to dark places!** So what is going on here? It's a combination of two things: interference of light from the **two slits** *plus* diffraction of light from **within each slit**.

Let's look at the interference part first. Suppose that the width of the slits,  $a$ , are tiny, tiny, tiny relative to the distance,  $d$ , between the slits. Then the light interferes only due to its traveling to the screen from two different starting points (the two slits) and does not include diffraction from

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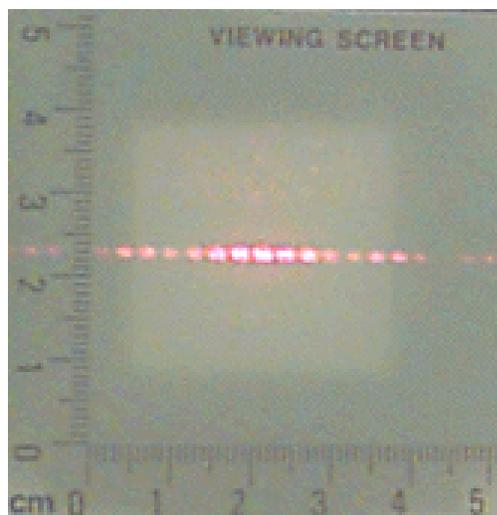


Figure 9.6: Diffraction and interference pattern produced by laser light passing through a double-slit.

within a single slit. For the interference only case, the intensity distribution looks like what is plotted in Fig. 9.7. The figure has lots of equally spaced bright-dark-bright-dark fringes, like a “picket fence”.<sup>2</sup>

If we make the slits larger and larger so that they are not small relative to the distance between them ( $a \approx d$ ), then we get the image pattern shown in Fig. 9.8. Now the interference effect between two slits competes with the diffraction effect from one slit. Notice how Fig. 9.8 is a combination of the interference “picket fence” from Fig. 9.7 and the diffraction effect from Fig. 9.3. Where there is no light reaching the screen because of diffraction, the picket fence goes to zero. Only where diffraction allows light to make it to the screen will the interference pattern be visible.

We want to come up with an Interference Equation for the double-slit, similar to the Diffraction Equation for the single-slit. For the single-slit we used the diffraction minima (dark spots), now we will use the interference maxima (bright spots) and the equation:

$$d \sin \theta_m = m\lambda. \quad (9.5)$$

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<sup>2</sup>Here’s a link to a Java simulation of interference: <http://ngsir.netfirms.com/englishhtm/Interference.htm>.

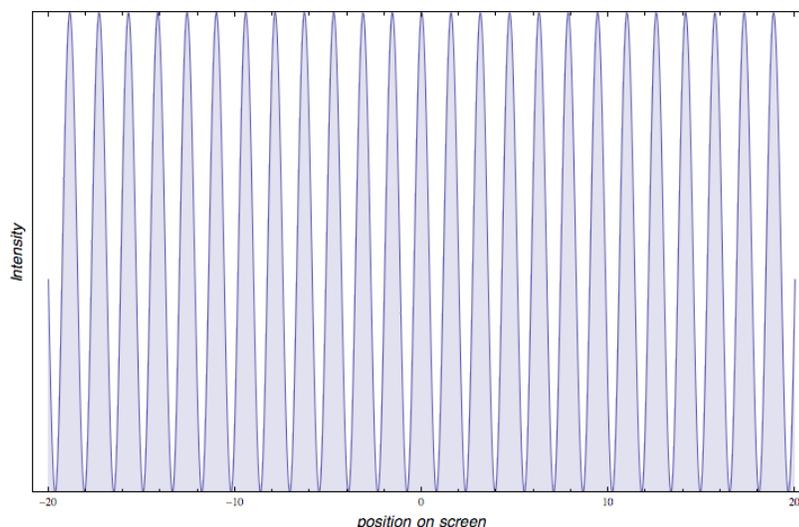


Figure 9.7: Intensity of light from only the two slits interfering with each other, not from the light from different edges of the same slit.

where  $d$  is the distance between the center of the slits,  $m$  is the order number of the interference maximum (bright spot),  $\theta_m$  is the angle from the center line to the  $m$ th interference maximum and  $\lambda$  is the wavelength of light. Fig. 9.9 shows a diagram of the double-slit setup and labels relevant variables. In the upper diagram the laser light is coming from the left, shining on a double-slit of slit spacing  $d$  and then traveling a distance  $D$  to the screen. Using trig and the small angle approximation as before Eq. 9.5 can be rewritten as

$$d = \frac{m\lambda D}{x_m}. \quad (9.6)$$

where  $d$  is the distance between the slits,  $x_m$  is the distance between the central maximum and the  $m$ th interference maximum (bright spot). Note that the algebra looks the same as Eq. 9.4, except that  $x_m$  refers to the location of **maxima**, not minima, and  $d$  is the **spacing** between the two slits, not the width  $a$  of the slits.

The lower diagram in Fig. 9.9 shows the intensity distribution from the double-slit with examples of  $m$ th order interference maxima as well as  $n$ th order diffraction minima labeled.

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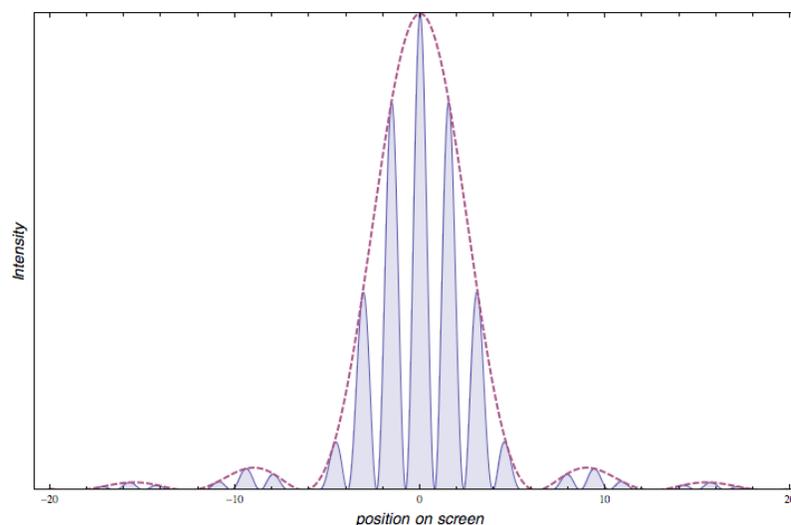


Figure 9.8: Intensity of light from a double-slit showing both the interference effect from 2 slits and the diffraction effect from within a slit. The diffraction pattern for a single-slit from Fig. 9.3 is shown overlaid as the dotted line.

If you look closely at Fig. 9.9 you'll see that as you go from the center peak to the right or left, the picket fence repeating pattern skips one. That's where the diffraction takes over and doesn't allow any light to interfere from the two slits. This may occur at exactly a picket fence point when

$$m = \frac{d}{a}, \quad (9.7)$$

where  $m$  is the order of interference **maximum**,  $d$  is the distance between the centers of the slits and  $a$  is the slit width. For the situation shown in Fig. 9.9, this happens exactly at

$$m = \frac{d = 5}{a = 1} = 5, \quad (9.8)$$

where the units of length are arbitrary in this calculation. This ratio refers to the 5th interference maximum from the center peak, which you can see is missing (remember that the counting starts with  $m = 0$  at the center). In this lab you will be able to see this happen. You'll see the picket fence and the places where the "slats" skip and then continue on.

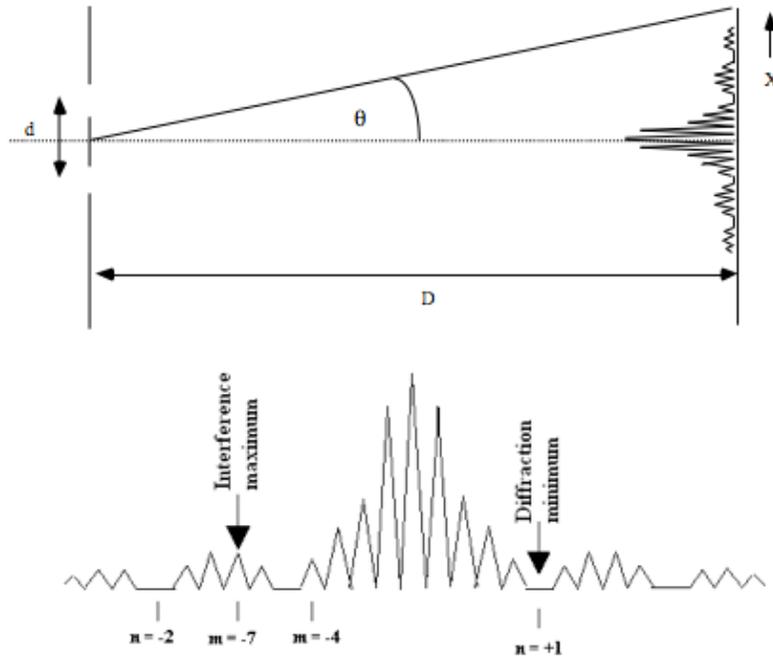


Figure 9.9: Geometry and intensity distribution for double-slit diffraction and interference. Arrows point to the  $m = -7$  interference maximum and the  $n = +1$  diffraction minimum. Note that the  $m = -5$  interference maximum is not seen here as it coincides with the  $n = -1$  diffraction minimum.

### Why don't we see diffraction in daily life?

The peak spacing (or picket fence effect) is **smaller** for **larger** object sizes. Common objects are much larger than the wavelength of light, so any interference effects are usually too fine to notice. Further, in every day life, we use light with a variety of wavelengths, so that peaks of one wavelength tend to land on valleys of another wavelength. Thus diffraction effects are not only too small for our eyes to resolve, but are also smeared out because the wavelength is not a single well-defined value. Using small objects with a single well-defined wavelength helps us see these effects in the lab.

## 9.5 In today's lab

The simplest diffraction and interference patterns involve plane waves (collimated or parallel light beams). Diffraction patterns associated with plane waves are called Fraunhofer patterns, named after the German scientist who first explained the effect. In this experiment, we will use a laser as our light source. A laser produces collimated and coherent light beams at one wavelength, which makes the interference patterns crisp and easy to see.

## 9.6 Equipment

- optics bench
- laser mounted on bench, wavelength  $\lambda = 650$  nm
- screen mounted on bench
- single-slit diffraction wheel
- multi-slit diffraction wheel
- rectangular frame with mount
- meter stick

## Safety Tips

The laser is a device that can produce an intense, narrow beam of light at one wavelength. **NEVER** look directly into the laser beam or its reflection from a mirror, glass, watch surface, jewelry, etc.

## 9.7 Procedure

You will collect one set of data for the group. **Write the names of all group members on the data sheet(s) and attach to one group member's lab report.**

## The single slit

As you do this part of the experiment, you should answer Questions 1–3.

1. Mount the single-slit wheel in the path of the laser beam (between the laser and the screen). The pattern is most easily seen with the slit near the laser and the screen far away. Try different slits and observe their diffraction patterns on the screen.
2. Choose a slit that gives a diffraction pattern of reasonable size. Measure the distance from the slit to the screen ( $D$ ) and record the labeled slit width in the Excel spreadsheet.
3. Attach a piece of paper across the screen where you see the diffraction pattern. Carefully mark the positions of the center of the principal maximum and the center of several orders of **diffraction minima** on either side of it. Remove the paper from the screen and attach it to your lab report, writing the names of all the group members on it. Answer Question 1.
4. Measure the distance of each minimum from the principal maximum ( $x_n$ ) and record them in the Excel spreadsheet. Have Excel calculate the slit width ( $a$ ) using Eq. 9.4. Remember to use negative  $x_n$  and  $n$  for the positions to the left of the principal maximum.
5. Have Excel calculate the mean value of the slit width and the standard deviation of the mean value. (The Excel formula for standard deviation of the mean is `=STDEV(cell11:cellN)/SQRT(N)`, where  $N$  refers to the total number of measurements). You can use the standard deviation of the mean value as the uncertainty in your slit width ( $\delta a$ ).

## Babinet's Principle

As you do this part of the experiment, you should answer Questions 4–6.

1. Place a thin wire in the laser beam.
2. Measure the distance between the wire and the screen ( $D$ ) and record the labeled wire diameter.

3. Tape a piece of paper to the screen. Mark the positions of the principal maximum and the **diffraction minima**.
4. Measure the distance of each diffraction minimum from the principal maximum and record them in the Excel spreadsheet. Have Excel calculate the diameter of the wire using the appropriate equation.
5. Have Excel calculate the mean value of the wire diameter and the standard deviation of the mean value.

### The double slit

As you do this part of the experiment, you should answer Questions 7–11.

1. Mount the multi-slit wheel in the path of the laser beam. Try different double-slits.
2. Choose a double-slit that gives a reasonable pattern. Measure the distance from the slit to the screen ( $D$ ) and record the labeled slit width  $a$  and slit spacing  $d$  in the Excel spreadsheet.
3. Tape a piece of paper across the screen where you see the pattern. Mark carefully the positions of the principal maximum, the **interference maxima**, and the **diffraction minima** on the paper. (You may want to distinguish the marks for each kind.) Remove the paper from the screen and attach it to your lab report and answer Question 7.
4. Measure the distance of each **interference maximum** from the principal maximum ( $x_m$ ) and record them in the Excel spreadsheet. Have Excel calculate the slit spacing using Eq. 9.6.
5. Have Excel calculate the mean value of the slit spacing  $d$  and the standard deviation of the mean value.



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3. Discuss the consistency of your mean value (and its uncertainty) of the slit width with the labeled slit width. Your TA will tell you what uncertainty to use for the labeled slit width.

### **Babinet's Principle**

4. Is the position right behind the wire light or dark? Why is this surprising?

5. What is the equation you will use to calculate the diameter of the wire? Clearly define each quantity.

6. Discuss the consistency of the mean value (and its uncertainty) of the wire's diameter with the labeled wire diameter. Your TA will tell you what uncertainty to use for the labeled wire diameter.



9. How does the slit width  $a$  affect the double-slit pattern?
10. How does the slit spacing  $d$  affect the pattern? Discuss what you expect to happen to the double-slit pattern based on Eq. 9.6. Then try it experimentally and describe what you saw on the screen.

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11. Discuss the consistency of the mean value (and its uncertainty) of the slit spacing  $d$  with the labeled slit spacing. Your TA will tell you what uncertainty to use for the slit spacing.