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Physics 214 – Lab 1

Interference and Diffraction

NAME: ____________________ ☐

LAB PARTNER(S): ____________________ ☐

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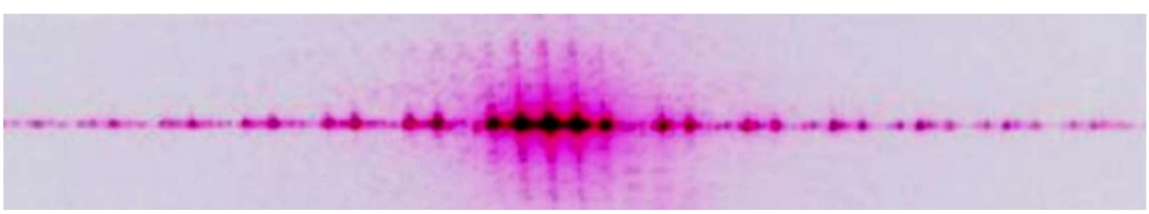
Check the box next to the name of the partner to whose report your group's data strips are attached.

LAB SECTION: ____________________

TA: ____________________

DATE: ____________________



Physics 214 Laboratory 1

Interference and Diffraction Patterns

Equipment

He-Ne laser, Power < 5 mW with mounting claw clamps
Green laser, Power < 5 mW with mounting clamp
Pasco slit set (three sets of slits mounted on glass slides) with positioning stand
Viewing screen on mounting post
Optical bench with five sliding mounts
Ruler
Paper strips
2 binder clips
Meter stick, 2-meter stick
Desk lamp
Blank CD on a mount with post
Cardboard strip with paperclip for hair measurement

Caution: Never look straight into the laser beam or into a specular reflection of the laser beam. The latter occurs when the laser beam strikes the glass PASCO slide. Keep your head away from direct or reflected beams. Do not insert mirrors, jewelry, or any smooth reflecting surface, etc., into the laser beam. Do not remove either laser from its mount.

Theory:

Because it can be described as an electromagnetic wave, light can display interference, specifically diffraction: light can be transmitted (or reflected) by various openings (e.g., slits) in a screen, or even by parts of a single opening. The light from each of these "sources" independently would create some intensity pattern on a distant screen, where the intensity is just proportional to the square of the wave amplitude – the electric field, in the case of light. For sinusoidal waves in particular, $I = A^2/2$. However, when the sources are all present simultaneously, the waves from the different sources can interfere, and the intensity is then proportional to the square of the *net* amplitude, summing together the amplitudes from all the contributing sources. In some places they will interfere constructively, leading to a higher intensity; in other places they will interfere destructively, leading to a reduced – or even zero – intensity.

For simplicity, we consider the case of two interfering sources. If their individual amplitudes and intensities are the same ($I_1 = A_1^2/2 = A_2^2/2 = I_2$), the total intensity is given by $I_{tot} = 4I_1 \cos^2(\varphi/2)$, where φ is the phase difference between the two waves at the detector. Often this phase arises from the geometry of the system – light from one source had to travel farther to get to the detector than light from the other source. If the path length difference is δ, the relative phase is $\varphi = 2\pi\, \delta/\lambda$, where λ is the wavelength of the light (assumed to be identical for the two sources). We will have complete constructive interference when $|\varphi| = 0, 2\pi, 4\pi\ldots$ (corresponding to a path length difference $|\delta| = 0, \lambda, 2\lambda,\ldots$) and complete destructive interference ($I_{tot} = 0$) when $|\varphi| = \pi/2, 3\pi/2\ldots$ (corresponding to a path difference $|\delta| = \lambda/2, 3\lambda/2,\ldots$).

For example, if light is incident on two slits (as shown in Fig. 1a) φ is the phase difference for the light traveling to a point on the screen from either the top or the bottom slit (which are separated by slit spacing d). Obviously, φ (and therefore the intensity) depends on where we look on the screen. Assuming the screen is far away from the slits ($L >> d$), we see from simple geometry that $\delta = d \sin\theta$; the transverse location on the screen is just $y = L \tan\theta$. In most of our experiments the distance from the slits to the screen L (about 1 meter) is large compared to the width of the pattern on the screen that we will observe (about 8 cm) so that θ is small compared to one radian. Then we can approximate $\sin\theta \approx \theta \approx \tan\theta$. We can therefore use $\theta \approx y/L$ in the above expressions to relate y, the position on the screen, to φ, and use this to calculate the locations of interference fringe maxima or minima:

$$\varphi = 2\pi \frac{d\,y}{\lambda L}\,.$$

In Fig. 1b we consider light passing through a *single* opening of width a, which we can think of as a large number of infinitesimal slits. The diffraction of the light will result in a pattern as shown. It turns out that for this case it is much easier to calculate the locations of the intensity *minima*. We can do this by finding the location (the angle θ) such that light from each point on the top half of the slit destructively interferes ($\varphi = \pi$, $\delta = \lambda/2$) with light from the bottom half. Since the average separation of the top and bottom halves is $a/2$, we have $\delta = (a/2)\sin\theta$, and the first diffraction minimum is at $\sin\theta_{min} = \lambda/a$. Similarly, one can show that the nth minimum is at $\sin\theta_{min,n} = n\,\lambda/a$. As before, we can use $y = L\tan\theta$ (possibly with the small angle approximation) to determine where the diffraction minima are located on the screen.*

With these definitions the intensity of the light on the screen is a function of y, the distance along the screen; λ, the wavelength of the light; and d, a, and L, which are the geometric parameters of the experiment. In this laboratory you will measure the locations of the peaks and zeroes of the intensity distribution. You will find how the intensity pattern changes for different values of slit width, a, and slit separation, d. And you will use this knowledge to make some precision measurements.

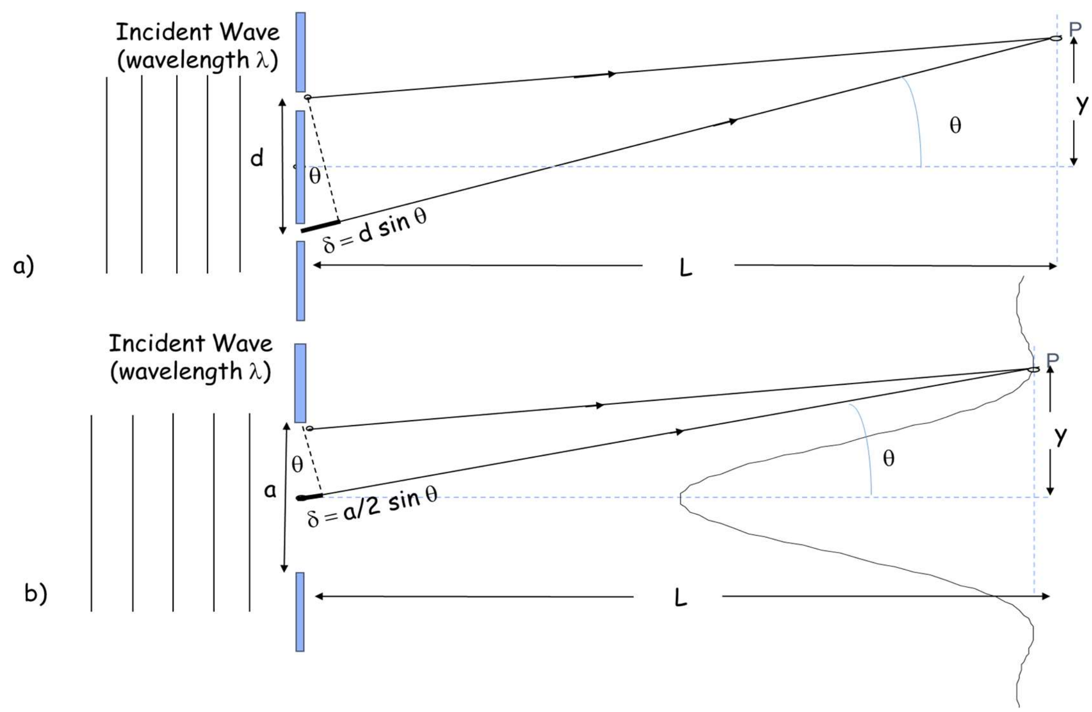


Figure 1.

The organization of this lab is as follows: You will first (**Activity 1**) make some preliminary observations using a laser and various diffraction slits to improve your qualitative understanding of the phenomenon. You will then (**Activity 2**) make a more *quantitative* comparison between theory and experiment. Next (**Activity 3**) you will use this knowledge to make some "useful" measurements

* Note that each slit in a multi-slit opening will produce its own diffraction 'envelope'; for closely spaced slits these envelopes all overlap each other, and the final pattern is the product of the single-slit diffraction envelopes and the multiple-slit interference pattern.

of the width of your hair! Finally (**Activity 4**), you will explore how a grating can greatly increase the measurement resolution and be used to find the wavelength of an unknown laser.

Activity 1 Interference and diffraction, qualitative

Do not look into the laser beam or into its reflection off of surfaces. The lasers we use in 214 can damage your eye if the beam goes straight in. Specifically, because the beam is collimated and coherent, it is possible to deposit all of the energy on just one or two cells on your retina, which could damage them! So NEVER look directly into any laser, and please take care not to send stray laser beams and reflections around the lab room. Avoid reflecting the laser beam off wristwatch crystals or jewelry.

A.) Single-Slit Diffraction

Almost all of your investigations will be made with the green laser. It may have been lowered at the end of the previous lab section and the slit-slide holder may not be in position. Raise the green laser in its post holder. With the laser pointed toward the screen, turn on the green laser by holding down its push button. You should see a bright spot of green light on the screen. Now put the slit-slide holder in place and insert the PASCO slide with four single slit patterns (#9165A). (Note that the width *a* of the slits is written on the slide.) Adjust the height of the slit-slide holder and the horizontal position of the slide so that the laser is incident on the *widest* slit D (160 microns) as shown in Figure 2 below.

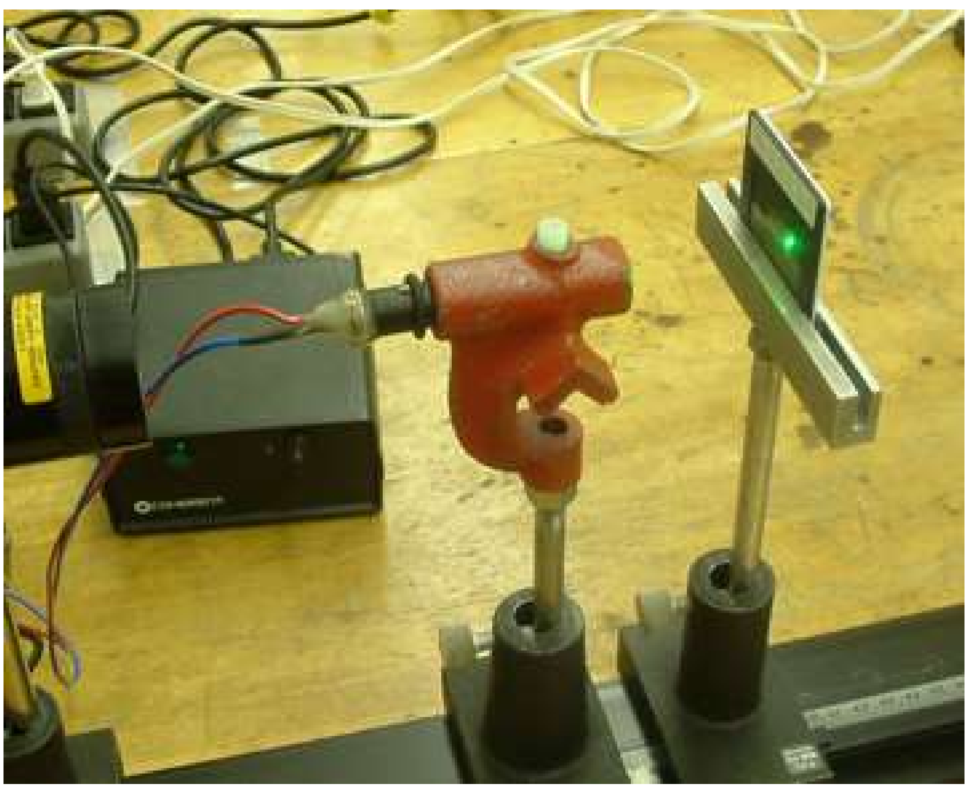


Figure 2. Green laser.

For ease of viewing, you may need to turn on your desk lamps and ask your TA to turn off the ceiling lights. Observe the pattern on the screen. What you are observing is known as **"diffraction"** – the interference of light through an opening or scattering by a finite-sized object.

Prediction	What do you predict will happen to the pattern as you progressively direct the laser onto the narrower slits C, B, and A of widths 80, 40, and 20 microns, respectively? Put checks next to your choices in the box below. (We won't grade you on your predictions here or later on. There is no need to erase incorrect guesses!) Pattern will get **narrower** ___ **wider**___ when going to narrower slits. Intensity of the pattern with get **brighter** ___ **dimmer** ___ when going to narrower slits.

Now do the experiment. Progressively direct the laser onto the narrower slits C, B, and A of widths 80, 40, and 20 microns respectively and observe the diffraction patterns of each.

Q1 Describe briefly how the pattern changed as the slit width was changed (comment on both the width *and* the intensity of the profile.) Do the results agree qualitatively with the theoretical predictions for single-slit diffraction?

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ASIDE: In this course you will learn that light waves are actually composed of tiny packets of energy known as photons. Photons have specific energy E and momentum p. How can a single particle like a photon display the interference behavior that you just observed? The answer is found in the principal subject of this course -- Quantum Mechanics -- which says that particles also have wave properties. In this context, what you have just observed is a fundamental demonstration of the "Heisenberg Uncertainty Principle" of quantum mechanics ($\Delta x\ \Delta p_x \geq \hbar/2$, where $\hbar$ is Planck's constant divided by 2π), as it applies to the photons in the laser beam! In words, the Heisenberg Uncertainty Principle says that it is impossible to know both the momentum and the position of a particle with absolute precision -- the better you know one, the more uncertain the other becomes. A narrower slit better defines the transverse position Δx of the photon. This then necessarily increases the transverse momentum Δp_x of the photon, resulting in a wider angular divergence. We will discuss these ideas later in the course.

Next you will observe the interference of light passing through more than one slit**.**

B.) Double-Slit Interference/Diffraction

Find the PASCO slide with four double-slit patterns (#9165-B). Note that the slit separation *d* is written on the slide. Place the slide into the mount in front of the laser, adjusting it so that the laser is incident on the pair of slits A with the *narrowest* separation (0.25 mm). Observe the pattern that you see on the screen. This is a double-slit interference pattern (underneath an overall single-slit diffraction "envelope").

Prediction	Compared to the double-slit pattern with d = 0.25 mm, what do you predict will happen to the pattern when you direct the laser onto the double slits with d = 0.50 mm? ____ ____

Move the slide so the laser overlaps pattern B, and **observe** the new interference pattern.

Q2 When the separation of two slits is increased, does the spacing of the principal maxima increase, decrease, or remain the same?

The spacing of the principal maxima: increases, decreases, remains the same. (circle one)

In technical terms, the **series of bright interference lines** are called **"fringes"**. Finally, let's see the effect of adding more slits.

C.) Multiple-Slit Interference/Diffraction

Find the PASCO slide with N = 2, 3, 4, and 5 slit patterns (#9165C). For these patterns the slit width and spacing is constant; only the number of slits is changing. Start by illuminating the *double-slit* pattern A (N=2) with the laser.

Prediction	What do you predict will happen to the pattern as you progressively direct the laser onto the patterns with more slits? ____ ____

Now carefully observe the interference when you direct the laser onto the 3-, 4-, and 5-slit patterns.

Q3 Describe briefly how the pattern changes as the *number* of slits is increased. What happens to the distance between the principal maxima? Could you notice any difference in the *intensity* of the principal maxima? What about the *width* of the principal maxima?

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What you have just observed is the basic multi-path interference phenomenon that we will see again in the context of diffraction gratings. One overall principle is that the size of the *smallest* (i.e., narrowest) feature observable in the interference pattern on the screen is inversely proportional to the size of the *largest* (i.e., widest) feature of the slits. Again, this is a direct consequence of wave interference (which underlies the Heisenberg Uncertainty Principle).

Activity 2 Practical Metrology (study of measurements) via Interference

In Activity 1 you gained an intuition for optical interference. Now we want to confirm the formulas we use to make quantitative calculations.

Move the PASCO slide (#9165C) so the laser is again illuminating the double-slit case. Use a pair of binder clips to attach a strip of paper (available in the front of the room) to the screen so that the interference pattern is on the paper. Using a meter stick or a 2-meter stick if necessary, measure the distance L from the slits to the screen:

L = _____meters

Using a pencil [do *not* use a shiny pen -- we don't want beams scattering in random directions!], carefully mark the location of several of the interference *maxima* (make sure to mark at least 5 adjacent maxima). Now remove the paper from the screen, and with a ruler measure the distance between the pencil marks indicating the maxima (just record the total end-to-end spacing of your indicated maxima, and divide by the number of intervals [one less than the number of maxima!].

Total spacing = __________meters Number of intervals: __

Distance between maxima, Δy = _________meters

What is this distance theoretically? The maxima occur when the light from the two slits adds constructively, i.e., when the phase difference at the screen of the light coming from the slits is $2\pi n$ (where n = 0, ±1, ±2, etc.). This multiple of 2π phase difference occurs when the path length difference
$\delta = d \sin\theta = n\lambda$, where d is the slit separation and λ is the wavelength. (= 532 nm for the green laser)

Q4 Use your measured values of L and Δy to calculate θ, and then use this value of θ to calculate the slit separation d and enter it below. Show your work here:

Measured value of **d = ___________mm**.

Q5 What is the percentage difference between your measured slit separation, and the value stated on the slide? [%difference = $100|d_{measured} - d_{slide}|/d_{slide}$] What might be the cause of the difference?

%difference = ____________

Possible cause of difference =

____

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Next move the PASCO slide so that the 4-slit pattern is illuminated. Below draw a careful sketch of the pattern you observe, showing at least 2 principal maxima (the 'bright' spots).

Using a new paper strip, repeat the above measurements (marking only the principal maxima) and calculations.

Total spacing = _________meters **Number of intervals:___**

Distance between maxima, $\Delta y_{4\text{-slits}}$ = ________meters

Q6 Use your measured values of L and $\Delta y_{4\text{-slits}}$ to calculate θ, and the slit separation d. Show your work here:

Measured value of $\boldsymbol{d}$ = ________**mm**.

Q7 What do you conclude is the effect of adding more slits?

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Finally, switch back to the PASCO slide with four single-slit patterns (#9165A), and shine the laser on the narrowest slit. For this activity, you'll need to ask your TA to turn off the room lights and everyone will need to turn on their desk lamps. Repeat the above measurement using a third strip of paper, now measuring the location of the first diffraction *minimum* on either side of the central maximum. (We record *minima* here, because the diffraction maxima are actually not quite equally spaced.) Divide this by 2 to get the location of the minimum relative to the center of the pattern.

Total spacing = ________meters

Distance to first minimum, Δy = ________meters

Q8 In the space below, write the expression for the location Δy of the first diffraction minimum in terms of a (the width of the slit), L (distance to the screen), and λ (laser wavelength), and solve this for a using your measured values for Δy and L. You can also get a more accurate number by measuring higher order minima, instead of just the ones closest to center.

Measured value of **a = ________mm**

Q9 What is the percentage difference between your calculated slit width, and the value stated on the slide? [= $100|a_{measured} - a_{slide}|/a_{slide}$]

%difference = ________

Activity 3 Practical Metrology (study of measurements) via Interference

In the previous activity you (hopefully) verified the basic diffraction and interference formulas. Now let's use these to make some "practical" measurements. Specifically, you are going to measure the width of your hair. First, it is necessary for you to know/believe that the diffraction pattern for a narrow opaque strip is quite similar to that for a narrow slit of the same width†.

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†ASIDE: This is a specific instance of "Babinet's Principle": a hole (e.g., a slit) and a complementary object (e.g., an opaque strip of the same width) will have *identical* diffraction patterns in places on the screen where there would be no light in the absence of both hole and object. You might find this counterintuitive, instead thinking, perhaps, that the two would give patterns that were just the opposite of each other, i.e., where one had peaks the others would have minima. But it's not the case, and here's a simple explanation why. If there were no slit and no strip, then obviously there would be no interference pattern on the screen; moreover, the screen would be dark everywhere except the small region where the beam is. Remember that the intensity of light at any place is proportional to the *square of the electric field*. The electric field of the light at each point on the detecting screen *when neither slit nor strip is present* may be considered to be the sum of two components: E_{slit}, the electric field from the light that would

Paperclip one of your hairs[‡] to the strip of cardboard at your station; then mount this in the slit slide holder so that the hair is approximately vertical and the laser is diffracting around it. Again, use a pair of binder clips to attach a new strip of paper to the screen, so that the laser diffraction pattern of the hair is on the paper.

Q10 Compare the pattern you observe to that from the single-slit diffraction in Activity 1.

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Repeat the procedure from the previous activity to determine the width of your hair.

Total spacing between minima = __________meters Number of intervals: ___

Distance between minima, Δy = _________meters

Q11 Use the values you measured to determine the width of the hair:

Width of the hair = _________microns.

Activity 4: Measurements of a diffraction grating (a.k.a. a compact disk)

In lecture you covered/will cover the topic of a diffraction grating, which is nothing more than a series of closely spaced slits. Light incident on the grating interferes in such a way that certain colors can only go in certain directions. In this activity we will use a *reflection* grating. It is very similar to a transmission grating, except that the role of the slits is taken by closely spaced reflective strips (and as you saw in Activity 2, slits and strips give identical patterns).

have come through the slit, and E_{strip}, the electric field from the light that would have come around the obstacle. At points on the screen where the intensity is zero we thus have $I \sim (E_{slit} + E_{strip})^2 = 0$. So unless E_{slit} and E_{strip} are themselves equal to zero, it must be the case that $E_{slit} = -E_{strip}$. Therefore, $E_{slit}^2 = E_{strip}^2$ – the intensity patterns from the slit alone and the strip alone must be identical.

[‡] For the sample hair it is best to choose someone with dark hair (or at least not blonde). Why? Because some significant fraction of the laser light will actually *pass through the center* of lighter hair (where the light is incident at close to normal); less will be transmitted near the edge because the light there is incident at a grazing angle, and therefore highly reflected. Thus, instead of a single non-transmitting strip the width of the hair, the effect is to have two non-transmitting strips (the edges of the hair) separated by a partially transmitting region. To complicate matters further, because of its cylindrical cross section, the hair acts like a converging cylindrical lens on the transmitted light.

Consider the diagram in Figure 3. Light (a plane wave) is incident from the right. Each strip acts like a source of "Huygen's wavelets". Because the incident light is assumed to be a monochromatic plane wave, all the strips emit coherently with each other. And because the beam is normally incident, they all emit in phase. This is then precisely the same situation as occurs with a transmission grating – many adjacent slits, all emitting in phase.

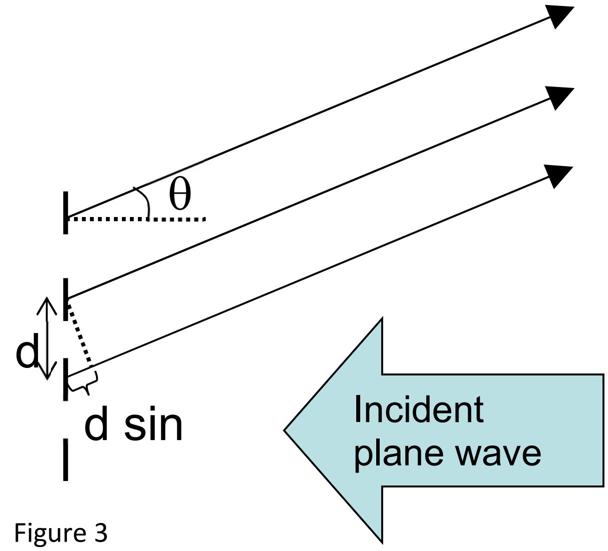

Figure 3

It is simple to find the direction of the first constructive interference maximum: this is the direction such that the light from one strip is exactly 2π out of phase with light from the two adjacent strips. From the figure we see this means that $(d \sin \theta) = \lambda$. Similarly, the position of the second interference maximum is given by $d \sin \theta = 2\lambda$, and so on. Note that this is the identical condition as for the interference maxima for a simple two-slit (or two-strip!) configuration. The effect of the other slits is *not* to change the location of the interference maxima. Rather, the destructive interference contributions from all the other slits acts to narrow the width of these maxima, i.e., so that the intensity profile is no longer given by $\cos^2(\phi/2)$, as it is for just two slits[§]. These narrowed peaks, and the fact that their intensity depends on N^2 (where N is the total number of slits/strips that are contributing), means they can be used to make very precise measurements, as you shall now demonstrate.

A.) Determine the spacing between the grooves on a CD/DVD.

An unburned CD/DVD has a continuous spiral reflective track on it. The process of "burning" the CD/DVD involves using a sharply focused laser to change the reflectivity along the track, thereby writing the strings of zeros and ones that encode the information. (When you play the CD/DVD, a different laser (wavelength = 780 nm) is used to measure the varying reflectivity along the spiral track, thereby reading out the information[**].)

Near the edge of the CD/DVD, the adjacent grooves of the track form a nearly parallel array of closely spaced reflective strips -- a reflection grating! Now you will measure the strip spacing.

- Do not have the laser turned on at first while you set this activity up.

[§] Roughly speaking, the width of the individual maxima (i.e., the *narrowest* feature that can be seen in the intensity pattern far from the grating) is inversely proportional to the overall region of the grating being illuminated, in precisely the same way – and for precisely the same underlying reasons – that the width of the central peak of a single-slit diffraction pattern is inversely proportional to the slit width.

[**] The readout laser is considerably weaker than the write-laser; otherwise, it would "erase" the disk while reading it!

- Remove the slit-slide holder from its post holder and insert the CD holder with the CD side facing the laser. Loosen the locking screw of the post holder to the rail and slide the post holder so that the CD is about 30 cm from the laser. Turn on the laser and adjust the CD mount so that the laser is incident on a spot where the grooves are vertical (see Figure 4). To make sure the disk is perpendicular to the beam, the zeroth-order diffraction peak (and also the reflection off the CD plastic coating) should bounce directly back toward the laser (they may be high or low, but should not deviate left or right). The light bouncing off the CD should be directed toward the *wall* of the classroom. See Figure 5.

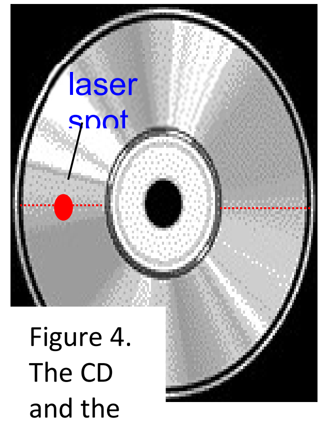

Figure 4. The CD and the laser spot (red).

PLEASE BE CAREFUL OF STRAY REFLECTIONS!

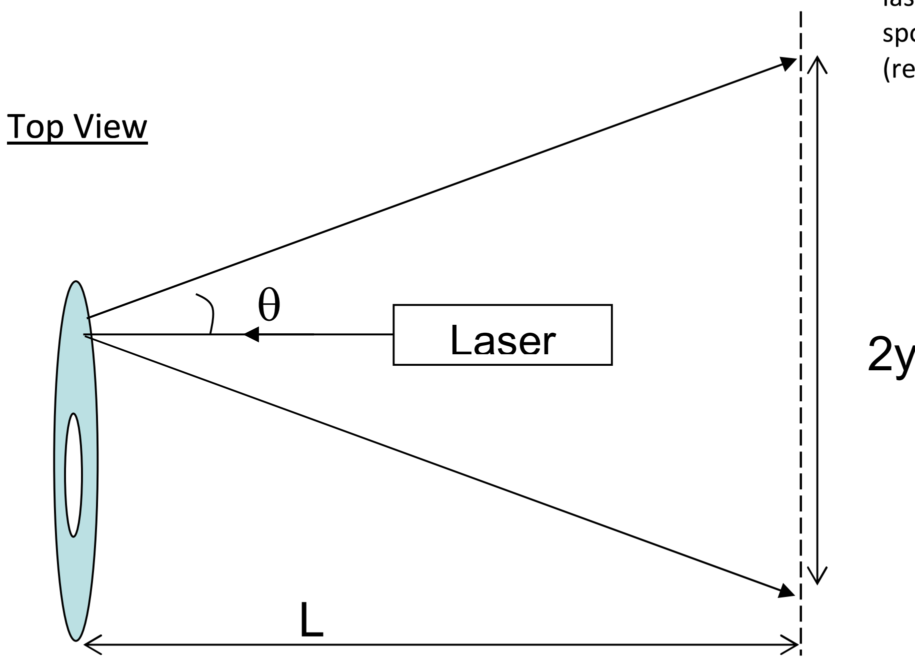

Figure 5. The direction of the reflected beams

- You should be able to clearly see both the 1st- and 2nd-order diffraction peaks. Measure the distance L between the CD and the wall:

L = ______________cm

- Now measure the distance between the *right* 1st-order and the *left* 1st-order peaks (i.e., between the +1 and -1 peaks as shown in Figure 4):

2 y = ______________cm

Q12 From these measurements, calculate the angle θ of the 1st-order peak (show your work below). **Notice:** Because the "slits" are very close together, the angle is large, so you cannot use the small angle approximation.

θ = ______________

Q13 Since the 1st-order peaks occur when (d sinθ) = λ, you can now calculate the separation between the reflective strips:

The spacing of the strips (i.e., between the grooves) is: ___________microns.

B.) A Better Spectrometer

You can use your measurements above to measure the wavelength of a HeNe laser. Lower the green laser so it does not block the light from the HeNe laser. Turn on the HeNe laser. (The on-off switch is a turn-switch on the laser power supply.) Note that it takes a few seconds for the laser light to come on - be patient! If the laser light does not come on after a few seconds, check to make certain that the shutter on the front collar of the laser is open!

Q14 Now knowing the spacing of the grooves on the CD, repeat the above measurements using the HeNe laser, calculate its wavelength, and record it below.

Show your work here:

HeNe laser wavelength λ = _________nm

C. Estimating the storage capacity of a CD/DVD[††].

Q15 The minimum spacing between the spots encoding zeroes and ones *along* the spiral track has a value similar to the spacing *between* adjacent tracks. From this information, estimate how many resolvable 0s and 1s a CD could have, by dividing the total recordable area of the CD (don't forget to subtract the central "hole" area!) by the area for an average pixel.

Show your work here:

I estimate the storage capacity of the CD to be ____________bits.

Q16 How does your estimate compare to the stated information storage capacity of ~700MB (remember, the "B" stands for "byte"; 1 byte = 8 bits)?

<u>Finishing the Report</u>

Congratulations. You have completed the first Physics 214 laboratory. If you have any comments, please enter them in the space below. Hand in your completed laboratory report to your teaching assistant. **One person in your group should staple the paper strips from Activity 2 and 3 to his or her report.** Check the box on the cover of the report indicating who has the strips. Please turn off <u>all</u> of your lab equipment!

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[††] DVDs can hold a lot more data than a CD, for several reasons. First, they use a laser with a slightly shorter wavelength (640 nm), which can therefore be focused to a smaller spot. Both the track-to-track spacing and spot-to-spot spacing for a DVD is about half that for a CD, leading to a factor of ~4 increase in storage capacity. By using both sides of the disc and 2 layers of data per side, DVDs can store more than 16GB. Blu-ray disc systems reduce the wavelength of the readout laser yet further to 405 nm, increasing the information storage capacity of a single disc to 50 GB (more with additional layers!) – enough for modern HD and 4K video.

APPENDIX

INTERFERENCE AND DIFFRACTION SET
PASCO SCIENTIFIC COMPANY

Single Slit Slide

Pattern	A	B	C	D
No. Slits	1	1	1	1
Slit Width	0 .02 mm	0.04 mm	0.08 mm	0.16 mm

Double Slit Slide

Pattern	A	B	C	D
No. Slits	2	2	2	2
Slit Width	0.04 mm	0.04 mm	0.08 mm	0.08 mm
Slit Space	0.25 mm	0.50 mm	0.25 mm	0.50 mm

Multiple Slit Slide

Pattern	A	B	C	D
No. Slits	2	3	4	5
Slit Width	0.04 mm	0.04 mm	0.04 mm	0.04 mm
Slit Space	0.125 mm	0.125 mm	0.125 mm	0.125 mm