Lab 5: Laser Optics

- **I.** Introduction
  - **A.** This lab is different from the previous labs in that it is a take-home exercise. This fact has several important consequences:
    - **1.** You'll do it on your own time, whenever you like, as long as you submit a lab report before the due date. The lab is due **one week** from the time you receive the equipment.
    - **2.** You'll borrow the equipment from us: an optics kit, a CD, and a meter stick. However, the kit is not cheap, so we will note your names and the number of the kit you borrowed, and we expect to get it back within a week's time. You do not want us to charge you something like $50 for a damaged, lost or otherwise unreturned optics kit, and frankly we don't want that either. So please return your equipment intact.
    - **3.** You'll still do the lab in groups of three. Make sure you have the contact info of your lab partners, so you can agree on a time and place to get together and do the lab. You will receive only one set of equipment per group, so you can't fly solo here. We expect you to work together both to do the lab and to write it up. Submit only one lab report per group.
    - **4.** If you need help doing the lab, we will provide help. A lab TF will be available for "help room" sessions from 7 to 10 pm on the following days:
      - **a.** Monday, April 23
      - **b.** Tuesday, April 24
      - **c.** Wednesday, April 25
      - **d.** Monday, April 30
      - **e.** Tuesday, May 1
    - **5.** The help room is SC 301. You can ask questions or even work through the entire lab there under the supervision of the TF. However, if you want to do the lab in the help room, you must:
      - **a.** come with all three members of your lab group; and
      - **b.** all have read the entire lab in advance.
  - **B.** What this lab is about
    - **1.** Measuring the wavelength of light
      - **a.** In the first part of the lab, you will use a steel ruler to measure the wavelength of the laser light. The laser produces a narrow, intense beam of monochromatic (that is, single-wavelength) light. The ruler has a shiny, metallic finish. Consequently, if you reflect the laser light off the surface of the ruler, it behaves like a mirror with the angle of reflection equal to the angle of incidence. However, if you shine the laser beam onto the part of the ruler where the black division marks are, a surprising thing happens: not only does the light reflect at the expected angle, but one observes that there are many *additional* reflections. One might wonder why the law of reflection suddenly seems to be violated just because there are some non-reflective marks on the ruler.
      - **b.** The answer turns out to involve interference between many different "sources." (For whatever reason, physicists have always referred to many-source interference phenomena as diffraction, but it's not a qualitatively different phenomenon from interference.) The basic idea is that when the light falls on the ruler, the shiny parts between the black markings act as new sources of light. Then the additional reflections you see are places where there is constructive interference from neighboring sources. As always, the condition for constructive interference is that the path difference is equal to an integer number of wavelengths.
      - **c.** The experimental setup is shown below in figure 1 (which is not to scale):

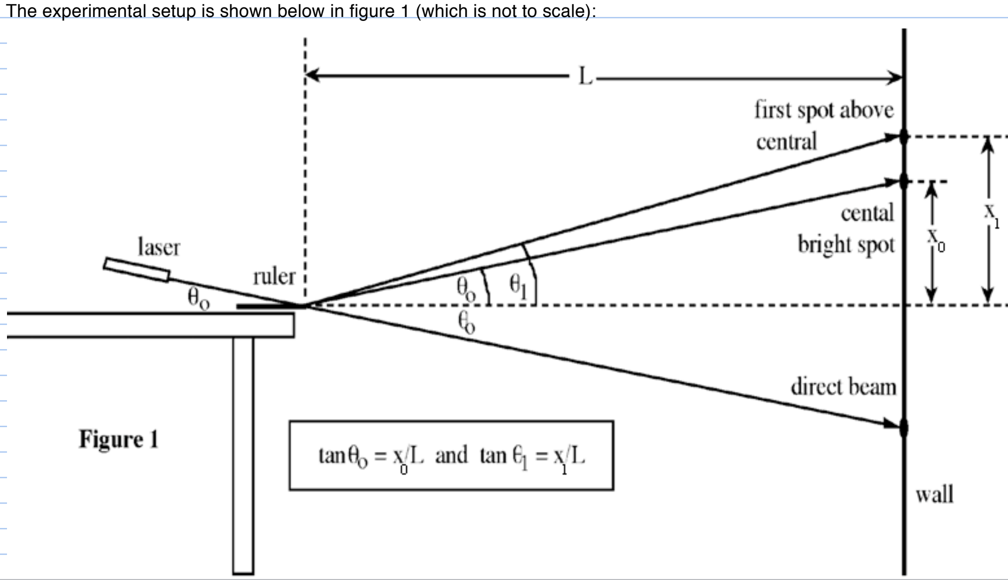

Figure 1

d. The ruler is placed on a table about 1 m (distance L) from the wall, and the laser is positioned so that the beam just strikes near the end of the ruler at a grazing angle. Part of the laser beam misses the ruler completely and continues undeviated to the wall ("direct beam"). Many reflections will appear on the wall, but, to keep the drawing simple, only two are shown in the figure. The brightest reflected spot, the central bright spot, corresponds to the reflection whose angle is equal to the angle θ_0. Many more reflection spots, above and below θ_0, will be present.

e.

Let us now apply the condition for constructive interference to our specific geometry. A more detailed illustration is presented in figure 2; again, only a few paths are shown to keep the diagram simple:

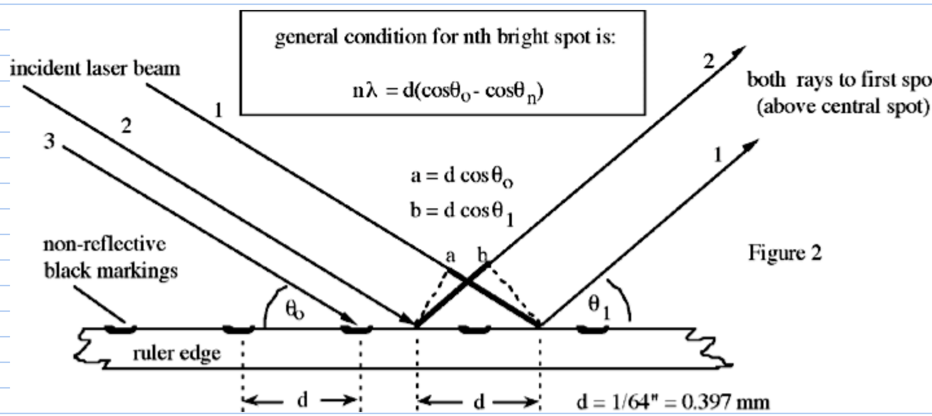

Figure 2

Incident laser beam rays, labeled 1 and 2, strike adjacent reflective surfaces on the ruler. Ray 3 happens to strike a black marking and we assume there is little or no reflection. The incident laser beam is actually is actually broad enough to be incident across several reflective and non-reflective areas of the ruler, but that does not change our analysis of where on the wall we can expect to have constructive interference. Important note: in the above diagram, rays 1 and 2 go to the same spot on the wall. They are drawn as being parallel (they both come off the ruler at the angle θ_1) because they *are* parallel, or at least almost exactly parallel, since they start out only 1/64" apart and end up at exactly the same spot after traveling a great distance (the wall is far away). The diagram does *not* show rays traveling to different positions on the wall.

f. The path length difference between rays 1 and 2 can be calculated as follows: the two rays have equal length until they reach the first dashed line. Then ray 2 changes direction, while ray 1 travels onward a distance $a = d \cos \theta_0$ (marked in bold). After that, ray 2 travels a distance $b = d \cos \theta_1$ before reaching the second dashed line. From that point on, the path lengths are again equal for the two rays. So the path difference is $d (\cos \theta_0 - \cos \theta_1)$. For constructive interference, this must be an integer number of wavelengths:

$n\lambda = d (\cos \theta_0 - \cos \theta_1)$

In the diagram, the outgoing rays end up at the first bright spot above the central bright spot, so n = 1. More generally, at the n^{th} bright spot (located at an angle θ_n), we have:

$\mathbf{n\lambda = d (\cos \theta_0 - \cos \theta_n)}$

That is the condition for constructive interference.

g. The central bright spot itself corresponds to n = 0, and in that case the angle of incidence is equal to the angle of reflection. Thus, it is in the same position where you would see the only bright spot if the ruler were uniformly shiny. It is possible to have both positive and negative n, although in your experiment you may not see both (depending on your angle of incidence). Positive n means that $\cos \theta_0$ is greater than $\cos \theta_n$, which actually means θ_n is larger than θ_0, so the bright spot will be above the central bright spot. Conversely, negative n corresponds to bright spots below the central bright spot.

h. You may have noticed something peculiar about the equation in bold. Visible wavelengths are between 400 and 700 nm, and d = 1/64" ≈ 0.4 mm, so λ is roughly 1000 times smaller than d. How is it then, that we are able to see distinct spots for n = 1, 2, etc. rather than having to go up to n = 1000? The answer is that $(\cos \theta_0 - \cos \theta_n)$ must be very small indeed. One way to accomplish this is by having the angles extremely close together; however, this would make the maxima very closely spaced and hard to measure. Instead what we do is take very small angles. cos θ changes very little with θ when θ is small (this is the flat part of the cosine curve, near the maximum at θ = 0.) So the key is to direct the laser light onto the ruler at *grazing incidence*. This allows the angles to be far enough apart to distinguish the different bright spots, while still maintaining a tiny value of $(\cos \theta_0 - \cos \theta_n)$. (Note that θ is complementary to the angle of incidence, which is near 90°. Also note that the angles in figures 1 and 2 have been greatly exaggerated for clarity.)

2. Determining the amount of data on a CD

a. Once you know the wavelength of the laser light, you can use it as a "ruler" to measure the track spacing on a compact disc. Then you'll be able to determine the data capacity of a CD.

b. The bottom surface of a CD is a highly reflective area containing a spiral of "pits." A high-powered electron microscope image of the CD surface is shown in figure 3 below. The scale line in the lower right is 2 microns long.

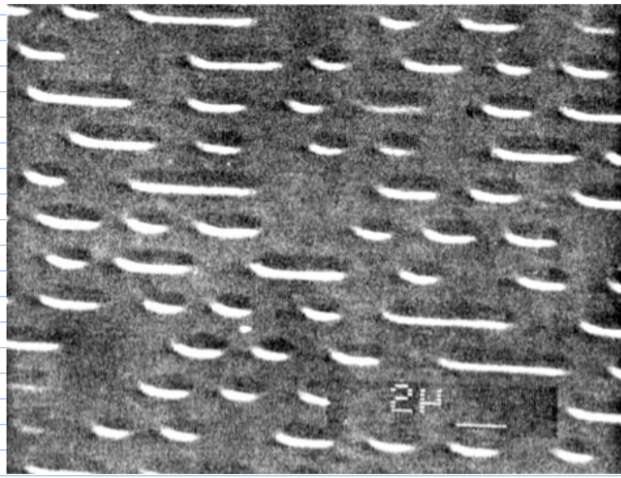

Figure 3

c. The length and separation of the pits encodes the digital information (whether audio information or just data, as on a CD-ROM) on the disc. Thus these quantities (pit length and pit separation) are irregular. However, the separation between adjacent "tracks" is very regular, and this is what you will measure. See figure 4 below:

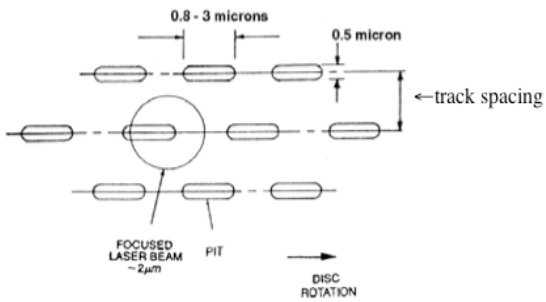

Figure 4

d. The setup you will use to measure the track spacing is essentially the same as you used in the previous part: the laser light is incident on a surface which is mostly shiny and reflective but contains evenly-spaced non-reflective markings. In the first part, these markings were the 1/64" black markings on the ruler; this time, it is the pits located along the tracks which are non-reflective (or at least, less reflective).

e. The big important difference is that the spacing, d, is now comparable to λ rather than being three orders of magnitude larger. This means two things:

- **(1)** You won't see many bright spots, just a couple.
- **(2)** You don't need (or want) grazing incidence. You want normal incidence instead.

f. The experimental setup is shown in figure 5 below:

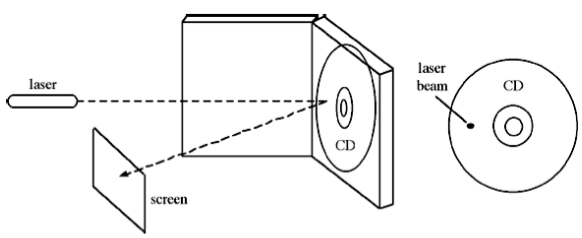

Figure 5

g. A close-up of the situation is shown in figure 6 (not to scale):

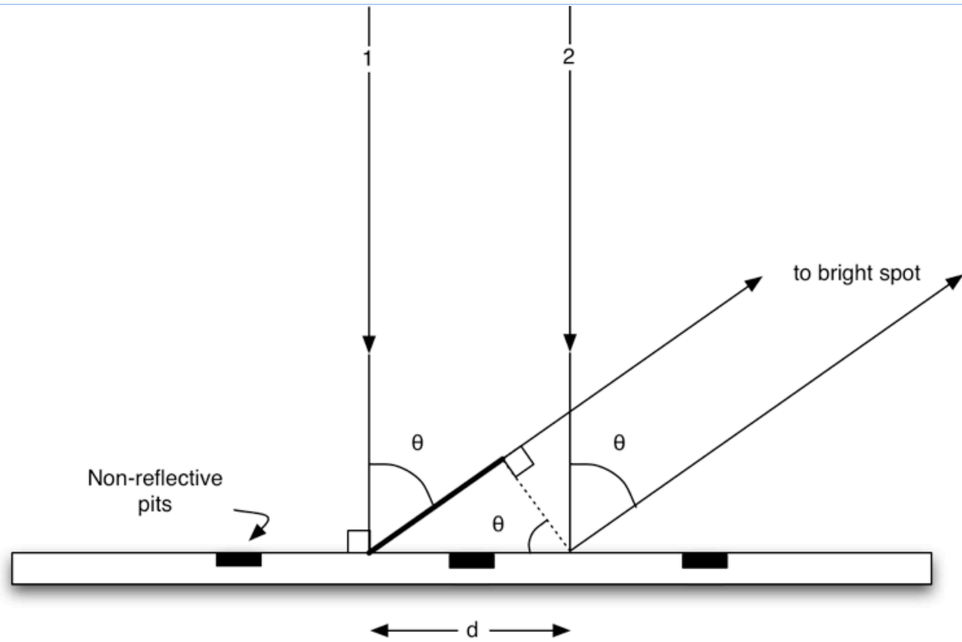

Figure 6

- **h.** The laser light is normally incident on the CD surface and the light comes off at an angle θ to the normal. (Again, both rays are very close to parallel and travel to the same spot.) The path difference (the distance traveled by ray 1 but not ray 2) is shown in bold and has a length of d sin θ. So the condition for constructive interference is
  $n\lambda = d \sin \theta_n$.
  For n = 0, this just means the central bright spot is directly back in the direction of the beam (i.e. it follows the law of reflection, just as n = 0 did for the ruler). You can also see from the equation that you will only see maxima for n small enough that nλ is no larger than d (otherwise, sin θ would have to be greater than 1, which is impossible).
- **i.** By the way, if you are wondering why it was cosine before and it's sine now even though the geometry didn't change, it's because in the first part we were measuring angles with respect to the horizontal, and now it's with respect to the normal.
- **j.** Thus by measuring the angles of the bright spots, you can determine d, the track spacing. Once you know d and the physical size of a CD, you can calculate the amount of data that can be stored it from the following specifications:
  - **(1)** On average, there is one bit of information encoded every 0.6 μm along the track length.
  - **(2)** There are 8 bits in a byte.
  - **(3)** There are 4 bytes per stereo sample (on an audio CD).
  - **(4)** The standard sampling rate for audio data is 44 kHz, that is, 44000 samples per second of recorded audio.

II. Materials

- **A.** Optics kit
  - **1.** Class 2 red laser
    - **a.** By now you should all have seen the video on laser safety, so you know what not to do. Most importantly, **never** shine the beam into your eye or anyone else's eye. That's pretty much the only dangerous thing you can do with the laser.
    - **b.** The laser beam turns on when you depress the button. While you are making measurements, you can keep the beam on by attaching a clothespin to the button. However, when you are doing anything else, please conserve the battery by turning the laser off. Your optics kit does not contain spare batteries.
  - **2.** Shiny metal ruler
    - **a.** The ruler has two sides: one side has 1/10" and 1/50" markings, and the other has 1/32" and 1/64" markings. You want to be sure to use the side with 1/64" markings.
    - **b.** The unmarked parts of the ruler surface are highly reflective and will act like a mirror. The black markings are non-reflective.
  - **3.** Clothespins
- **B.** Compact disc
- **C.** Meter stick

III. Procedure

- **A.** Measuring the wavelength of light
  - **1.** Setup
    - **a.** Set up the laser and ruler as in figure 1. Allow the ruler to slightly overhang the edge of the table, making sure that the ruler points perpendicular to the wall.
    - **b.** Adjust the angle of the laser beam so that it is incident upon the 1/64" markings on the laser. The grazing angle should be a few degrees (you do not need to measure it exactly, but it should be small). To adjust the angle of the laser beam, prop up the back of it on something thin like a notebook.

- **c.** You should see a series of bright red spots on the wall: the direct beam as it passes by the laser, the central bright spot, and several more bright spots which might be above or below the central bright spot. Once you have everything set up correctly, it is much easier to see the spots (and more that you hadn't noticed) if you turn the room lights off.
- **d.** If you see a lot of fuzziness or extra light, try the following:
  - **(1)** Make sure the laser light is not hitting the tabletop directly, only the ruler. (Hence why we hang the ruler over the edge of the table.)
  - **(2)** Also make sure that it is only on the edge of the ruler, where the markings are every 1/64 of an inch, rather than further in, where they are every 1/32" (because the 1/64" lines are short).
  - **(3)** If you still see extraneous light, try raising the grazing angle slightly.

2. Measurement

- **a.** Tape a sheet of paper to the wall and mark the locations of all the bright spots, labeling them as you go.
  - **(1)** The direct beam is always the lowest--it is the only one below the level of the table. Label it with a D.
  - **(2)** Label the central bright spot x_0. If you can't tell which one is the central bright spot, it should be the brightest spot except for the direct beam. If you still can't tell, see what happens when you move the ruler so that the laser beam falls only on the shiny part.
  - **(3)** If there are bright spots between x_0 and D, label them x_{-1}, x_{-2}, etc. (-1 is the one just below 0, -2 is below that, and so on.) If you can't see any bright spots below the central bright spot, that's fine too.
  - **(4)** Label the remaining bright spots (above x_0) as x_1, x_2, etc. Keep going as long as you can see bright spots. You can sometimes see 15 or 20 under the right conditions. You should have a minimum of 5 labeled x's.
- **b.** Turn off the laser and remove the sheet of paper from the wall.
- **c.** Using the meter stick, measure L (the distance from the ruler to the wall) as best you can.
- **d.** Locate the origin on your sheet of paper. (Hint: it is halfway between the direct beam and the central bright spot.) This corresponds to the height of the ruler. It is also the point from which all your x values will be measured. Mark the origin on your paper and label it with an O.
- **e.** Now that you are done using the ruler as a reflective diffraction grating, you may use it as a ruler. (I know, I know.) For every labeled x on your sheet, measure the distance from it to the origin and record it in a data table. It's fine to make those measurements in inches, since after all your very high-precision ruler is marked in fractions of an inch. You can convert them to cm later.

3. Analysis

- **a.** You may or may not want to use Logger Pro for this. It's your call, but I would recommend using it. Certainly it makes some things easier (calculated columns and graphs). If you decide to do everything by hand, that's fine. If you use Excel or another software package, that's also okay, but be warned that it is definitely not easy to get Excel to do what you want in terms of graphs and especially fitting.
- **b.** For each x_n, calculate the corresponding value of $\cos \theta_n$. (You will need to refer to figure 1.) Remember that these angles are all small, so cosine is very close to 1. Keep more significant figures than you think you need, because the whole reason we are using small angles is that $\cos \theta$ changes very little for small θ. It's quite likely that all of your bright spots will have a $\cos \theta_n$ between 0.99 and 1. So those third and fourth (and maybe fifth and sixth) decimal places are pretty important.
- **c.** Make a graph of $\cos \theta_n$ versus n. Fit a line to your data. Calculate the slope and intercept of the line. Also calculate the uncertainty of the slope.
- **d.** Use this information to calculate λ, the wavelength, along with the uncertainty of your calculation. (You may assume that there is no uncertainty in the distance d.)

B. Determining the amount of data on a CD

1. Setup

- **a.** Arrange the laser and CD so that the laser light is incident normal to the CD surface. (Be sure you are using the bottom surface of the CD.) You should see a reflected beam pointing directly back towards the laser, and a few other bright spots at different angles.
- **b.** The line along which the bright spots are located will be perpendicular to the tracks on the CD surface. The tracks themselves are laid out in concentric rings, so the diffraction pattern will be parallel to the direction of the radial line on the CD at the point where the laser beam strikes. (This makes more sense when you are doing it than reading about it.) So if you want a horizontal diffraction pattern, and you probably do, be sure to aim the laser beam at "3 o'clock" or "9 o'clock" on the CD.
- **c.** There are all kinds of ways to do this measurement and any of them is fine. Some examples are:
  - **(1)** Affix the CD to the ceiling, facing down, and shine the laser up on it; record the locations of spots on the table (or floor).
  - **(2)** Put the CD face-up on the table and shine the laser down on it; record the locations of spots on the ceiling.
  - **(3)** Stand the CD upright using the hinged case, and have the laser beam horizontally incident on the CD.
- **d.** If you arrange things *very* carefully, you can probably even manage to have the bright spots fall directly onto the meter stick itself, which will save you the hassle of having to mark up your table or floor or ceiling and then measure the distance between spots. There is a good consistency check here: to make sure that the meter stick is perpendicular to the reflected beam, put the direct reflection ($\theta_0 \approx 0$) at the midpoint of the meter stick and make sure that the first bright spots on either side ($\theta_{\pm 1}$) are equidistant from the middle. If they are not, rotate the meter stick about its midpoint until they are.
- **e.** You should also be able to see spots corresponding to θ_2 and θ_{-2}, although they are further apart and somewhat dimmer. However, you will not need to use those spots to measure the track spacing.

2. Measurement and analysis

- **a.** However you want to do it, the goal is to measure the angle θ_1 (and θ_{-1}, but it's just $-\theta_1$), and the easiest way of doing so is by measuring x and L just as you did in the first part. (x is the distance between bright spots on the meter stick; L is the distance from the meter stick to the CD.)

- **b.** Again, $x/L = \tan\theta$, but this time you want $\sin\theta$ instead of $\cos\theta$.
- **c.** Once you have $\sin\theta$, you can use your knowledge of λ from the previous part to derive d, the track spacing.
- **d.** Then you can calculate the track *length*, which is sort of like asking how long the spiral track would be if you could somehow "unwind" it all the way. (Hint: track length times track spacing equals the area of the data portion of the disc.) You may need to use your ruler to make some measurements of the size of the CD.
- **e.** From this information you can now calculate how much information you can store on a CD-ROM, or how many minutes of music can be recorded onto a CD.

IV. Lab report

For the lab report, submit your responses to the following questions on a sheet of paper. You should turn in one lab report per group.

A. Measuring the wavelength of light

- **1.** Explain why we had to use grazing incidence instead of normal incidence in order to see the interference spots.
- **2.** Derive an expression for $\cos\theta_n$ in terms of x_n and L.
- **3.**
  Write down the equation which expresses $\cos\theta_n$ in terms of n. Explain why it is a straight line when you graph it. What is the slope? What is the intercept?
- **4.** What is the wavelength of the laser light? Is this a reasonable answer? (For instance, if the wavelength does not correspond to red visible light, it is not a reasonable answer!)
- **5.** What is the uncertainty in your calculation of λ? Where did you get this value? Does it matter that you didn't estimate uncertainties for L, or any of the x values?
- **6.** Include your sheet with the spot markings, and all of your data (including the measurement of L), calculations, and graphs.

B. Determining the amount of data on a CD

- **1.** Without making any measurements, you can narrow down the possible values of d (the track spacing) just by observing that you can see the second-order bright spot, but not the third-order. Based on this observation, what range of values of d are possible?
- **2.** Briefly describe your experimental setup and what measurements you made in order to calculate θ_1. Include a diagram if that would be helpful.
- **3.** What is the track spacing on the CD? Is this a reasonable answer? Does it fall within the range of possible values you determined from question 1?
- **4.** Assume that you know θ_1 to within 1°. How much uncertainty does this introduce into your knowledge of $\sin\theta_1$? (Hint: you can use the general formula for error propagation, or you can just calculate the sine of the angles 1° higher and lower than your actual value.) How much uncertainty does that mean for d?
- **5.** What is the area of the recordable space on the CD surface? What is the total track length?
- **6.** From the specifications given in the introduction, how many megabytes (1 MB = 10^6 bytes) of data can be burned onto a CD-ROM? How many minutes of music can be recorded onto a CD? You should find that your answers are actually several times larger than the standard capacity of a CD. This is because a great deal of redundant information is always recorded, for the purposes of error detection and correction.

C. Make sure to include the following information at the top of your lab report:

- **1.** All of your names
- **2.** Your lab time
- **3.** Your optics kit #