Physics 6C Lab Manual

UCLA Physics and Astronomy Department

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Introduction

OVERVIEW

This lab series is very similar to the Physics 6A and 6B series. Please refer to those lab manuals for general information.

Important: This manual assumes that you have already taken the Physics 6A and 6B labs, and that you are familiar with Microsoft Excel. In addition, it assumes that you are able to perform all the operations associated with Data Studio (particularly for Experiment 5); call up sensors; use them to take various measurements; produce, title, label, and vary the appearance of graphs; perform calculations on the measured variables in Data Studio, and use the results to create graphs.

Note to TAs: You should have taught a Physics 6A lab section before teaching a 6C lab. If you have not, you should make sure that you have gone through all the Data Studio operations for an experiment (particularly Experiment 5) before teaching it.

Note to Instructors: The thermodynamics experiment, Experiment 5, requires two lab sessions to complete. It consists of two parts: a measurement of absolute zero using the Ideal Gas Law, and an experiment with a heat engine. For the experiment to be assigned two sessions, you would have to make the request at the beginning of the quarter, and possibly omit the radioactivity or photoelectric experiment. If you take no action, the default option is that the experiment will be assigned one session, and the students will just do the absolute zero measurement. (Later in the quarter up to the week before the experiment, you could request that the students do the heat engine part of the experiment instead of the absolute zero measurement.

It is essential that you follow the general rules about taking care of equipment and reading the lab manual before coming to class.

As before:

Lab grade =	(12.0 points)
	− (2.0 points each for any missing labs)
	+ (up to 2.0 points earned in mills of "additional credit")
	+ (up to 1.0 point earned in "TA mills")
Maximum score =	15.0 points

Typically, most students receive a lab grade between 13.5 and 14.5 points, with the few poorest students (who attend every lab) getting grades in the 12s and the few best students getting grades in the high 14s or 15.0. There may be a couple of students who miss one or two labs without excuse and receive grades lower than 12.0.

How the lab score is used in determining a student's final course grade is at the discretion of the individual instructor. However, very roughly, for many instructors a lab score of 12.0 represents approximately B− work, and a score of 15.0 is A+ work, with 14.0 around the B+/A− borderline.

POLICY ON MISSING EXPERIMENTS

1. In the Physics 6 series, each experiment is worth two points (out of 15 maximum points). If you miss an experiment without excuse, you will lose these two points.

2. The equipment for each experiment is set up only during the assigned week; you cannot complete an experiment later in the quarter. You may make up no more than one experiment per quarter by attending another section during the same week and receiving permission from the TA of the substitute section. If the TA agrees to let you complete the experiment in that section, have him or her sign off your lab work at the end of the section and record your score. Show this signature/note to your own TA.

3. (At your option) If you miss a lab but subsequently obtain the data from a partner who performed the experiment, and if you complete your own analysis with that data, then you will receive one of the two points. This option may be used only once per quarter.

4. A written, verifiable medical, athletic, or religious excuse may be used for only one experiment per quarter. Your other lab scores will be averaged without penalty, but you will lose any mills that might have been earned for the missed lab.

5. If you miss three or more lab sessions during the quarter for any reason, your course grade will be Incomplete, and you will need to make up these experiments in another quarter. (Note that certain experiments occupy two sessions. If you miss any three sessions, you get an Incomplete.)

Microwave Optics

APPARATUS

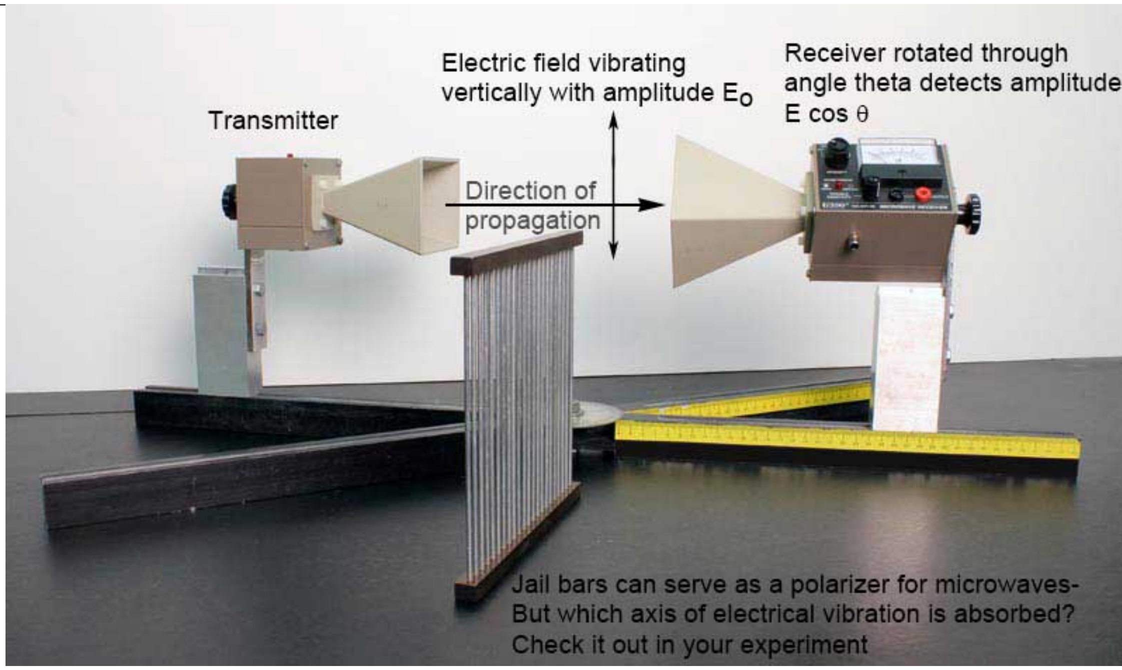
- DC analog microammeter
- Microwave transmitter
- Microwave receiver
- Power supply
- Four-arm track with protractor and scale
- Ring stand with clamp
- Banana leads
- Triangular aluminum screens
- Flat aluminum screen
- Flat lucite screen
- Polarizer
- Single slit
- Double slits
- Assortment of materials: ceiling tiles, wood, metal plates
- Ruler

INTRODUCTION

In this experiment, you will test several optical aspects of electromagnetic waves such as polarization, reflection, and interference. The electromagnetic spectrum covers a wide range of frequencies. Visible light has a frequency of the order of 10^{14} Hz and wavelengths between 400 and 700 nm (1 nm = 10^{-9} m). Other well-known parts of the spectrum include radio waves (with frequencies near 10^6 Hz) and microwaves (with frequencies around 10^{10} Hz and wavelengths of a few centimeters). Microwaves can be generated easily and are particularly suited for laboratory investigations.

POLARIZATION, REFLECTION, AND ABSORPTION OF MICROWAVES

Electromagnetic waves consist of position-dependent and time-dependent electric and magnetic fields which are perpendicular to each other. These waves propagate in a direction perpendicular to both fields. In this experiment, we consider microwaves produced by a transmitter whose axis is vertical. The electric fields of these microwaves are therefore linearly polarized in the vertical plane and travel in the horizontal direction.



A receiver which detects such microwaves measures only the component of the incident electric field parallel to its axis. If the angle between the incident electric field (of *amplitude* E_0 and the receiver axis is θ, then the parallel component of the field has amplitude $E_0 \cos\theta$, as shown in the figure above. Since the *intensity* of a wave is proportional to the square of its amplitude, the intensity I measured by the receiver is related to the intensity I_0 of the incident wave by

$$I = I_0 \cos^2\theta. \tag{1}$$

Eq. 1 is known as *Malus' Law* and tells us how the intensity varies with angle between the transmitter and receiver.

A wave incident on a metallic surface will be reflected after striking the surface. The law of reflection states that the angle of reflection θ_r is equal to the angle of incidence θ_i: $\theta_\mathrm{r} = \theta_\mathrm{i}$. Note that both angles are measured with respect to the normal to the surface.

Microwaves which impinge upon an opaque material are either reflected by, transmitted through, or absorbed by the material. Let us denote the reflected, transmitted, absorbed, and total electric-field amplitudes by R, T, A, and E, respectively. The law of energy conservation tells us that the total energy of the incident microwaves is equal to the sum of the reflected, transmitted, and absorbed energies. Since energy is directly proportional to intensity and therefore proportional to the square of the electric-field amplitude, it follows that

$$E^2 = R^2 + T^2 + A^2 \tag{2}$$

or

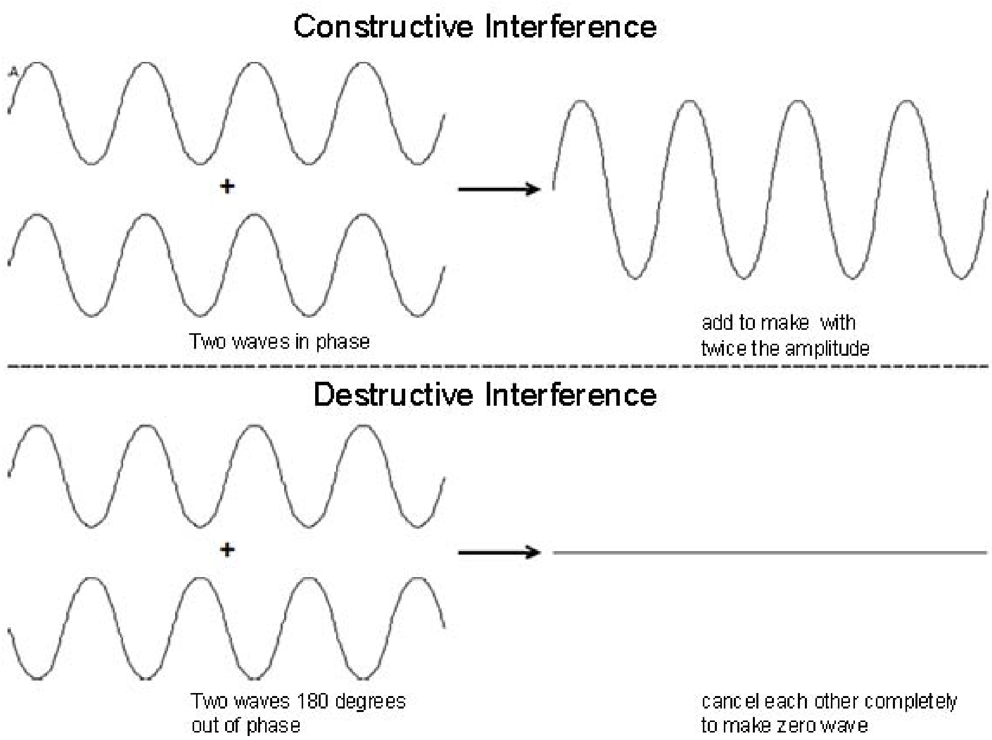
$$A^2 = E^2 - R^2 - T^2. \tag{3}$$

Thus, the percentage f_A of the incident microwave intensity absorbed by a material is

$$f_\mathrm{A} = [(E^2 - R^2 - T^2)/E^2] \times 100\%. \tag{4}$$

INTERFERENCE

When two separate waves occupy the same region of space, they combine with each other. According to the *superposition principle*, the displacement of the resultant wave is equal to the sum of the displacements of the individual waves. If the crests of the individual waves coincide with each other, then the amplitude of the resultant wave is a maximum, and the waves are said to undergo *constructive interference*. On the other hand, if the crest of one wave coincides with the trough of the other wave, then the amplitude of the resultant wave is zero at all points, and the waves undergo *destructive interference*. Waves that interfere constructively "build each other up" and have a maximum intensity, while those that interfere destructively "cancel each other out" and have a minimum intensity.



In this experiment you will build a device called a Michelson interferometer that splits a wave into two waves and then recombines the waves after they have traveled different distances. If the extra distance traveled by one of the two waves (called the *path difference*) is equal to an integral multiple of one wavelength (i.e., 0, λ, 2λ, etc.), constructive interference results, and the combined waves be measured to have a large intensity, as shown in the figure above. Conversely, if the path difference is equal to an odd integral multiple of a half wavelength (i.e., $\lambda/2$, $3\lambda/2$, $5\lambda/2$, etc.), destructive interference occurs, and the waves will cancel when they overlap and produce zero intensity.

INITIAL SETUP

You may find one of two types of microwave receiver/transitter setups at your station. Both of these setups use Gunn diodes to generate microwaves.

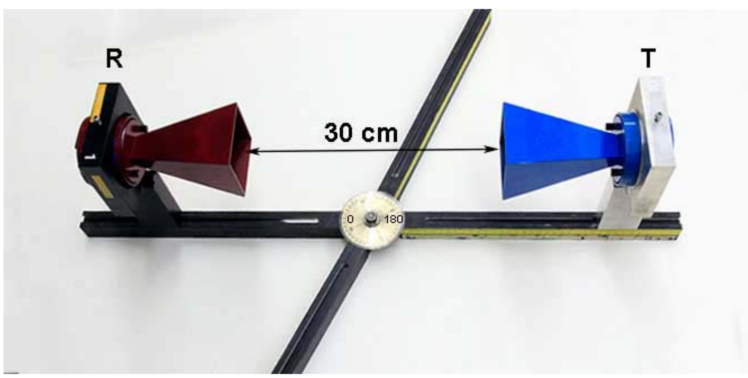
The most modern version, Pasco WA 9314B, is the easiest to use, and has a self-contained meter. Align the receiver horn facing the transmitter horn, and plug the transmitter in to turn it on. On the receiver, turn the intensity knob from “off” to “30”. Adjust the variable sensitivity knob for a full scale reading. You can increase the sensitivity later in the experimet if needed. When finished with the experiment, unplug the transmitter, and turn off the receiver.

The older Gunn diode unit uses a DC power supply for the transmitter, and a separate meter for the receiver. Be careful of the polarity from the power supply to the transmitter. The positive (red) connector of the power supply's output must be hooked to the positive (red) connector of the transmitter's input, or the diode will be destroyed. To adjust this device, place the receiver directly opposite the transmitter, and set the meter to minimum sensitivity. Turn on the power supply, and slowly increase the voltage until the diode begins to generate microwaves. You will notice that a further increase in voltage increases the output power until a plateau voltage is reached. After this point, an increase in voltage does not increase the output power. The transmitter should be operated at the beginning of this plateau. Never exceed 15 Volts DC, as doing so would destroy the Gunn diode.

The microwave receiver consists of a crystal diode which produces a current when aligned parallel to the electric field of the incident microwaves. The diode is not sensitive to microwaves whose electric field is perpendicular to its axis. The current from the diode is read by the horn. Be careful of the polarity between the receiver and the meter. The positive (red) connector of the receiver's output must be hooked to the positive (red) connector of the meter's input, or the meter movement may be destroyed. Never connect the receiver to the power supply, as this will destroy the diode instantly.

PROCEDURE

1. The microwaves emerging from the transmitter are linearly polarized in the vertical plane, and the receiver is sensitive only to the electric-field component parallel to its axis. Begin by recording the wavelength of the microwaves produced by the transmitter. Stand the transmitter and receiver vertically, with the two horns facing and approximately 30 cm apart from each other, as shown below.

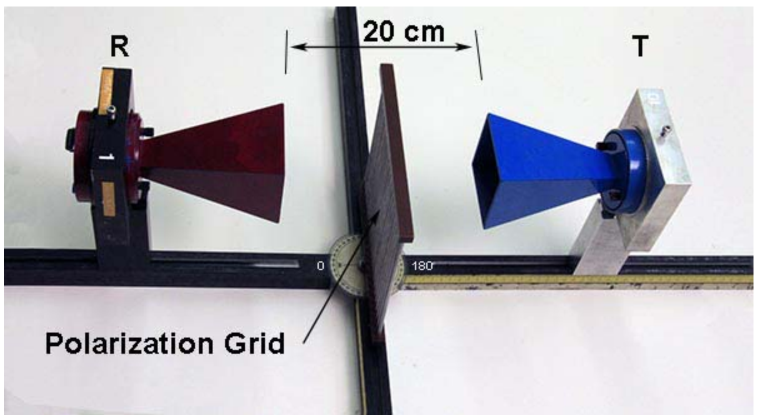


2. Connect the receiver to the meter, and align the transmitter and receiver horns such that the meter reading is a maximum. Adjust the sensitivity of the meter to read a convenient

value (e.g., 100) at the maximum, and take this orientation of the receiver to be $\theta = 0°$ in Eq. 1. Rotate the receiver in 5° increments, and record its reading for angles between 0° and 90° in the "Data" section. Since the meter measures the relative electric-field amplitude of the microwaves, you must square all readings to obtain the relative intensity I. Plot the experimental values of I as a function of θ.

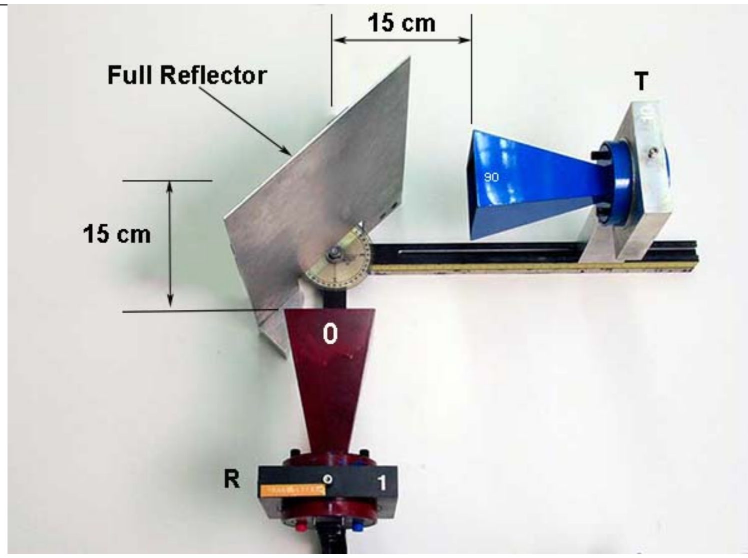
3. Using Eq. 1, plot the theoretical values of I as a function of θ. Comment on the extent to which your data agrees with or differs from Malus' Law.

4. Return the receiver to its vertical position. Place the polarization grid between the transmitter and receiver, as shown below.



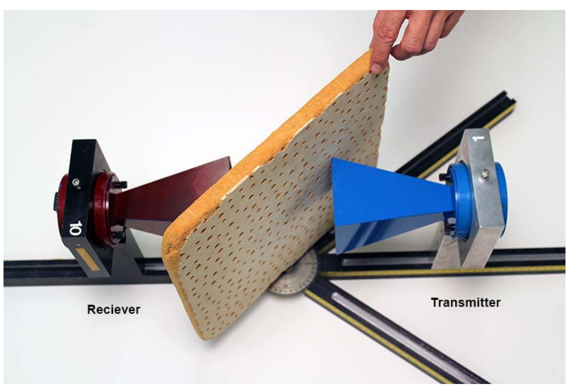
Rotate the polarization grid until it blocks all incoming microwaves, and note the orientation of the bars with respect to the incident electric field (i.e., either parallel or perpendicular). Explain what is happening. (This is not obvious. It has nothing to do with waves "squeezing between the bars", but has much to do with the fact that the bars are conductors. You may wish to refer to your data in step 6 for a hint.)

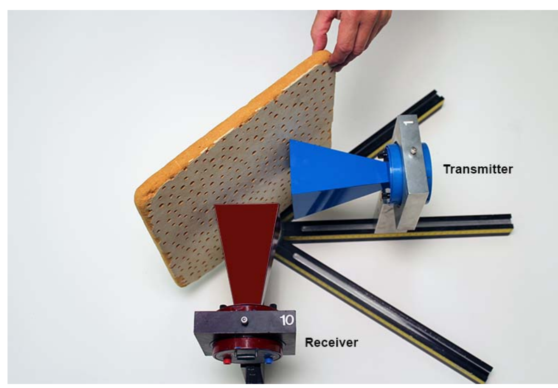
5. The reflection of microwaves by a full reflector (i.e., an aluminum plate) is measured with the setup shown below.



Place the transmitter approximately 15 cm from the reflector at an angle of incidence $\theta_\mathrm{i} = 30°$ (as measured by the protractor on the four-armed base). Vary the angle of the receiver (as measured by the protractor) until the meter reading is a maximum. Record this angle of reflection θ_r. Repeat the procedure for angles of incidence of 45° and 60°, measure the corresponding angles of reflection, and check the validity of the law of reflection.

6. Arrange the setup for absorption and reflection as shown below.

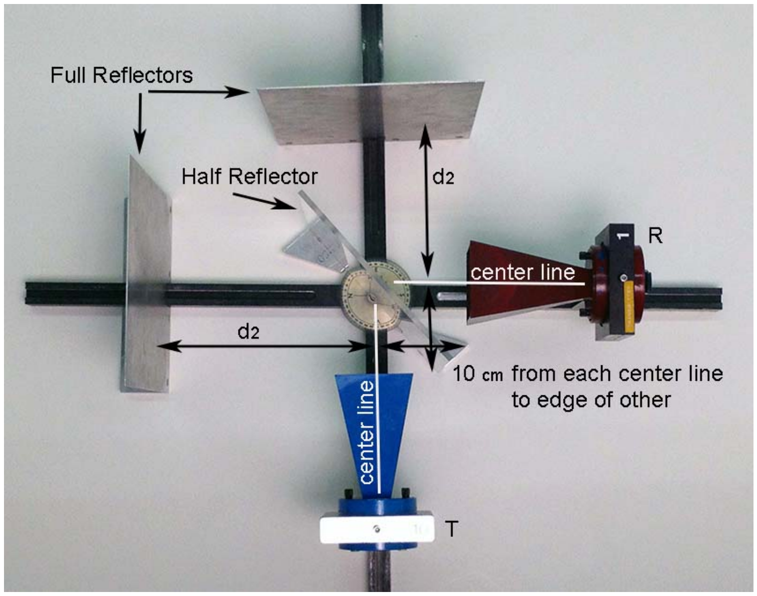




Place the transmitter and receiver horns facing and approximately 10 cm from each other. Adjust the sensitivity of the meter to read a convenient value (e.g., 100). This is the maximum electric-field amplitude (E) detected by the receiver. Place at least four different materials (two metal, one nonmetal, and lucite) at an angle of 45° with respect to the beam, and record the transmitted amplitude (T) for each material. Rotate the receiver so that it is at a right angle to the transmitter (as measured by the protractor), place the materials at an angle of 45° with respect to the beam, and record the reflected amplitude (R) for each material. Using Eq. 4, calculate the percentage f_A of the incident microwave intensity absorbed by each material.

7. The wavelength λ of the microwaves can be measured with the Michelson interferometer

shown below. (An interferometer is a device that can be used to measure lengths or changes in length with great accuracy by means of interference effects.)



The transmitter and receiver horns should each be approximately 10 cm from the center of the track. Place the two full (aluminum) reflectors at right angles to each other (as measured by the protractor) and at distances d_1 and d_2 from the center of the track. Place the half (lucite) reflector at an angle of 45° with respect to the incident beam. Adjust d_1 (the position of the full reflector opposite the receiver) until the receiver reading is a minimum. Next, adjust d_1 (the position of the full reflector opposite the transmitter) until the receiver reading is a minimum. Then vary d_1 between 15 cm and 40 cm, and record at least 15 values of d_1 for which the receiver output is a <u>minimum</u>. Knowing that the distance between adjacent minima is $\lambda/2$, calculate λ for each pair of adjacent minima, and determine the average wavelength. Compare this value with the wavelength recorded in step 1.

DATA

1. Wavelength of microwaves = ______________________________

2. Amplitude at $\theta = 0°$ = ______________________________

   Amplitude at $\theta = 5°$ = ______________________________

   Amplitude at $\theta = 10°$ = ______________________________

   Amplitude at $\theta = 15°$ = ______________________________

   Amplitude at $\theta = 20°$ = ______________________________

   Amplitude at $\theta = 25°$ = ______________________________

Amplitude at $\theta = 30°$ = ________________________________

Amplitude at $\theta = 35°$ = ________________________________

Amplitude at $\theta = 40°$ = ________________________________

Amplitude at $\theta = 45°$ = ________________________________

Amplitude at $\theta = 50°$ = ________________________________

Amplitude at $\theta = 55°$ = ________________________________

Amplitude at $\theta = 60°$ = ________________________________

Amplitude at $\theta = 65°$ = ________________________________

Amplitude at $\theta = 70°$ = ________________________________

Amplitude at $\theta = 75°$ = ________________________________

Amplitude at $\theta = 80°$ = ________________________________

Amplitude at $\theta = 85°$ = ________________________________

Amplitude at $\theta = 90°$ = ________________________________

Intensity at $\theta = 0°$ = ________________________________

Intensity at $\theta = 5°$ = ________________________________

Intensity at $\theta = 10°$ = ________________________________

Intensity at $\theta = 15°$ = ________________________________

Intensity at $\theta = 20°$ = ________________________________

Intensity at $\theta = 25°$ = ________________________________

Intensity at $\theta = 30°$ = ________________________________

Intensity at $\theta = 35°$ = ________________________________

Intensity at $\theta = 40°$ = ________________________________

Intensity at $\theta = 45°$ = ________________________________

Intensity at $\theta = 50°$ = ________________________________

Intensity at $\theta = 55°$ = ________________________________

Intensity at $\theta = 60°$ = ________________________________

Intensity at $\theta = 65°$ = ______________________________

Intensity at $\theta = 70°$ = ______________________________

Intensity at $\theta = 75°$ = ______________________________

Intensity at $\theta = 80°$ = ______________________________

Intensity at $\theta = 85°$ = ______________________________

Intensity at $\theta = 90°$ = ______________________________

Plot the experimental graph of I as a function of θ using one sheet of graph paper at the end of this workbook. Remember to label the axes and title the graph.

3. Plot the theoretical graph of I as a function of θ using the same sheet of graph paper. Remember to label the axes and title the graph.

4. Which orientation of the bars blocks all incoming microwaves? Why?

   ____

   ____

   ____

   ____

   ____

5. Angle of reflection for $\theta_{\mathrm{i}} = 30°$ = ______________________________

   Angle of reflection for $\theta_{\mathrm{i}} = 45°$ = ______________________________

   Angle of reflection for $\theta_{\mathrm{i}} = 60°$ = ______________________________

6. Maximum electric-field amplitude = ______________________________

   Material 1 = ____

   Material 2 = ____

   Material 3 = ____

   Material 4 = ____

   Transmitted amplitude for material 1 = ______________________________

   Transmitted amplitude for material 2 = ______________________________

   Transmitted amplitude for material 3 = ______________________________

Transmitted amplitude for material 4 = ______________________________

Reflected amplitude for material 1 = ______________________________

Reflected amplitude for material 2 = ______________________________

Reflected amplitude for material 3 = ______________________________

Reflected amplitude for material 4 = ______________________________

Percentage of microwave intensity absorbed by material 1 = ______________________________

Percentage of microwave intensity absorbed by material 2 = ______________________________

Percentage of microwave intensity absorbed by material 3 = ______________________________

Percentage of microwave intensity absorbed by material 4 = ______________________________

7. Positions at which receiver output is a minimum =

   ____

   ____

   Wavelength for each pair of adjacent minima =

   ____

   ____

   Average wavelength = ______________________________

   Percentage difference between average wavelength and value recorded in step 1 =

   ____

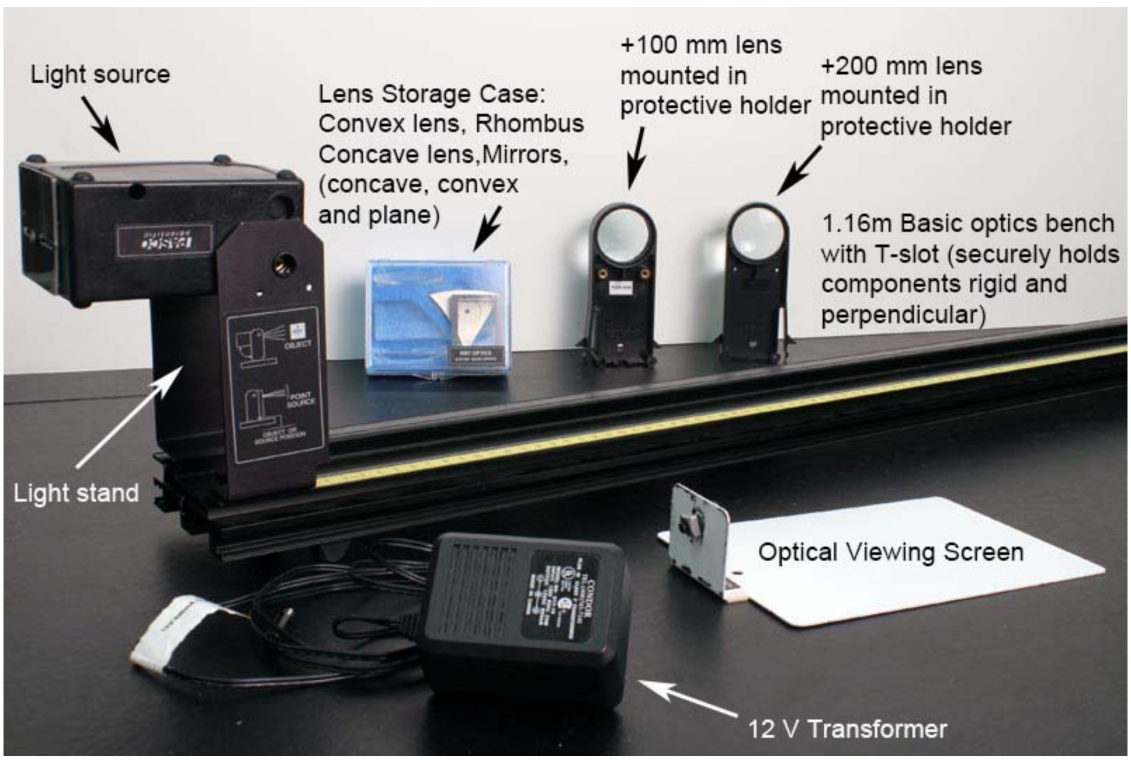
Geometrical Optics

APPARATUS

This lab consists of many short optics experiments. Check over the many pieces of equipment carefully:

Shown in the picture below:

- Optical bench with screen at one end and ray-box bracket at the other end
- Ray box with 12-V transformer
- Lens storage case with four items inside
- Four lens holders with +200 mm, +100 mm, +25 mm, and −25 mm lenses. (Two of these lenses are shown in the diagram below.)



Not shown in the picture above:

- Protractor and ruler
- Diverging lens with unknown focal length
- Card with fine print
- Graph paper
- Tape in room

If anything is missing, notify your TA. At the end of the lab, you must put everything back in order again, and your TA will check for missing pieces.

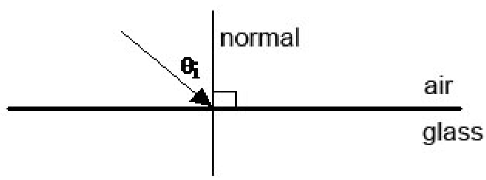
REFLECTION AND REFRACTION

When a beam of light enters a transparent material such as glass or water, its overall speed through the material is slowed from c (3×10^8 m/s) in vacuum by a factor of n (¿ 1):

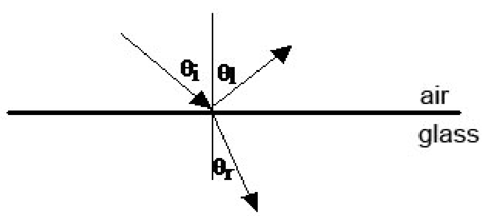
$$\text{(speed in material)} = c/n. \tag{1}$$

The parameter n is called the *index of refraction*, and is generally between 1 and 2 for most transparent materials. Even air has a refractive index slightly greater than 1.

Consider a light beam impinging on the boundary between two transparent materials (e.g., a beam passing from air into glass). By convention, the angle of incidence θ_i is measured with respect to the normal to the boundary.



In general, the beam will be partially reflected from the boundary at an angle θ_l with respect to the normal and partially refracted into the material at an angle θ_r with respect to the normal.



Fermat's Principle, which states that light travels along the path requiring the least time, can be used to derive the laws of reflection and refraction.

<u>Law of Reflection</u>:

$$\theta_\mathrm{l} = \theta_\mathrm{i}. \tag{2}$$

The angle of reflection θ_l is equal to the angle of incidence θ_i.

<u>Law of Refraction</u>:

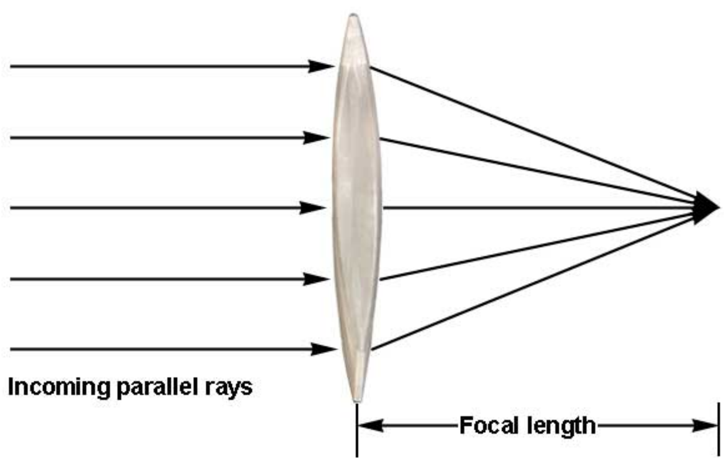
$$n_1 \sin\theta_\mathrm{i} = n_2 \sin\theta_\mathrm{r}. \tag{3}$$

This is also called *Snell's Law*, where n_1 is the refractive index of the material from which light is incident (air in this case), and n_2 is the refractive index of the material to which light is refracted (glass in this case).

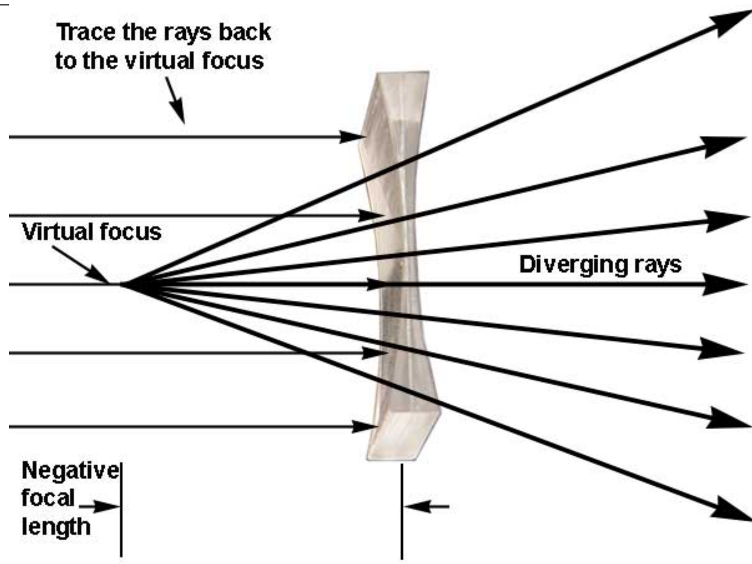
THIN LENSES

A thin lens is one whose thickness is small compared to the other characteristic distances (e.g., its focal length). The surfaces of the lens can be either convex or concave, or one surface could be planar. Because of the refractive properties of its surfaces, the lens will either converge or diverge rays that pass through it. A *converging* lens (such as the first plano-convex lens below) is thicker at its center than at its edges. A *diverging* lens (such as the second concave meniscus lens below) is thinner at its center than at its edges.

If parallel rays (say, from a distant source) pass through the lens, then a converging lens will bring the rays to an approximate focus at some point behind the lens. The distance between the lens and the focus of parallel rays is called the *focal length* of the lens.



If the lens is diverging, then parallel rays passing though the lens will spread out, appearing to come from some point in front of the lens. This point is called the *virtual focus*, and the negative of the distance between the lens and the virtual focus is equal the focal length of the diverging lens.



If an object (say, a lighted upright arrow) is placed near a lens, then the lens will form an image of the arrow at a specific distance from the lens. Let's call the distance between the lens and the object d_o, and the distance between the lens and the image d_i. Applying the Law of Refraction to the thin lens results in the *thin-lens equation*, which relates these quantities to the focal length f:

$$1/f = 1/d_o + 1/d_i. \tag{4}$$

Recall that f can be positive or negative, depending on whether the lens is converging or diverging, respectively. Once the object distance d_o is chosen, the image distance d_i may turn out to be positive or negative. If d_i is positive, then a *real* image is formed. A real image focuses on a screen located a distance d_i behind the lens. If d_i is negative, then a *virtual* image is formed. A virtual image does not focus anywhere, but light emerges from the lens as though it came from an image located a distance $| \; d_i \; |$ in front of the lens. You can see the virtual image by looking back through the lens toward the object. Such an image can be observed when you are looking through a diverging lens. These virtual images looks smaller and more distant.

CURVED MIRRORS

A curved mirror can also converge or diverge light rays that impinge on it. A converging mirror is concave, while a diverging mirror is convex. The mirror equation is identical to the thin-lens equation:

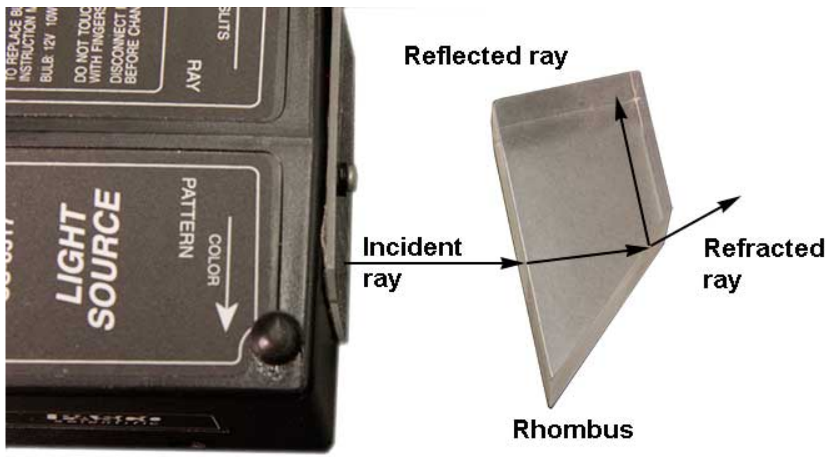
$$1/f = 1/d_o + 1/d_i. \tag{5}$$

We just need to remember that a real image with a positive image distance d_i will be formed on the same side of the mirror as the incident rays from the object, while a virtual image with a negative image distance d_i will be formed behind the mirror.

PROCEDURE PART 1: REFRACTION AND TOTAL INTERNAL REFLECTION

1. Place the ray box, label side up, on a white sheet of paper on the table. Plug in its transformer. Adjust the box so that one white ray is showing.

2. Position the rhombus as shown in the figure. The triangular end of the rhombus is used as a prism in this experiment. Keep the ray near the point of the rhombus for the maximum transmission of light. Notice that a refracted ray emerges from the second surface, and a reflected ray continues in the acrylic of the rhombus.



3. The incident ray is bent once as it enters the acrylic of the rhombus, and again as it exits the rhombus. Vary the angle of incidence. Does the exiting ray bend toward or away from the normal? (Physicists and opticians measure the angles of the rays with respect to the *normal*, a line perpendicular to the surface.)

   Does the exiting ray bend toward or away from the normal? ___________________________

4. Pick an angle of incidence for which the exiting ray is well bent, and trace neatly the internal and exiting rays on the top half of the paper underneath. Also trace the rhombus-air interfaces, clearly marking the side corresponding to the rhombus and that corresponding to air. You can simply mark the ends of the rays and use a ruler to extend the rays. Use the protractor to construct the normal to the interface and measure the angles of the two rays with respect to the normal. With these angles, use Snell's Law to find the refractive index of the acrylic of the rhombus. (Use $n = 1$ for air.)

   Angle of ray in acrylic = ______________________________

   Angle of ray in air = ______________________________

   Refractive index (n) of acrylic = ______________________________

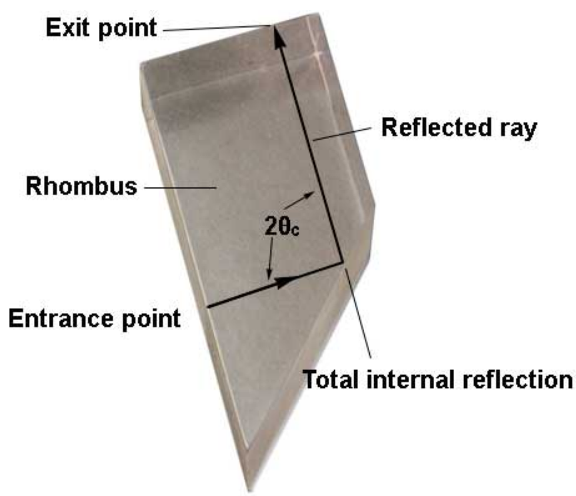
   Show your calculation of n below:

____

____

____

5. Total internal reflection: Rotate the rhombus until the exiting ray travels parallel to the surface (separating into colors), and then rotate the rhombus slightly farther. Now there is no refracted ray; the light is totally internally reflected from the inner surface. *Total internal reflection* occurs only beyond a certain "critical angle" θ_c, the angle at which the exiting refracted ray travels parallel to the surface. Rotate the rhombus again, and notice how the reflected ray becomes brighter as you approach and reach the critical angle. When there is both a refracted ray and a reflected ray, the incident light energy is divided between these rays. However, when there is no refracted ray, all of the incident energy goes into the reflected ray (minus any absorption losses in the acrylic).



Adjust the rhombus exactly to the critical angle, and trace neatly the ray in the acrylic and the refracting surface on the bottom half of the paper. Construct the normal to the surface, and measure the critical angle of the ray. (Again, all angles are measured with respect to the normal.) According to the textbook, the sine of the critical angle is

$$\sin\theta_c = 1/n. \tag{6}$$

Calculate n from this relation, and compare it to the n determined in step 4.

Measured critical angle θ_c = _________________________

Refractive index (n) determined from critical angle = _________________________

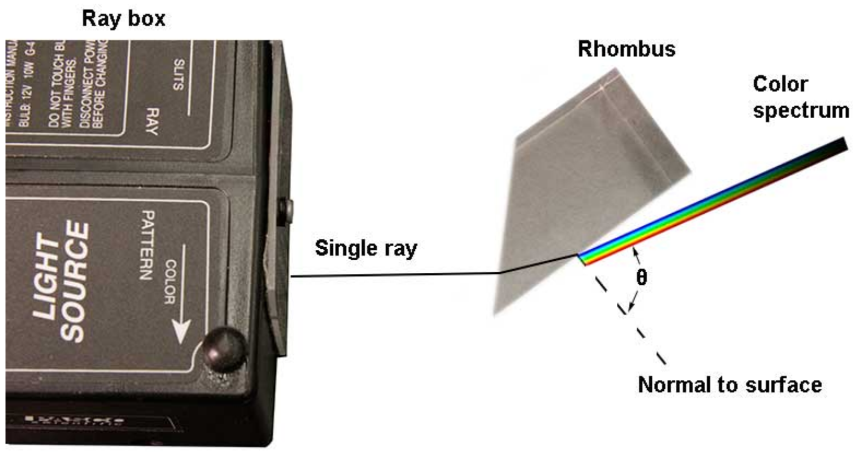
Refractive index (n) determined from Snell's Law (copy from step 4) = __________________

6. Adjust the rhombus until the angle of the exiting ray is as large as possible (but less than the critical angle) and still clearly visible, and the exiting ray separates into colors. This

phenomenon is called *dispersion* and illustrates the refraction of different colors at various angles. Which color is refracted at the largest angle, and which color is refracted at the smallest angle?

Color refracted at largest angle = ______________________________

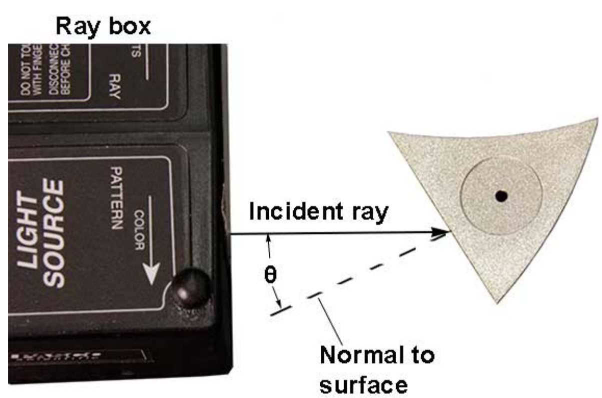
Color refracted at smallest angle = ______________________________



PROCEDURE PART 2: REFLECTION

1. As in the preceding section, the ray box should be on a white sheet of paper, label side up, with one white ray showing.

2. Place the triangular-shaped mirror piece on the paper, and position the plane surface so that both the incident and reflected rays are clearly seen.



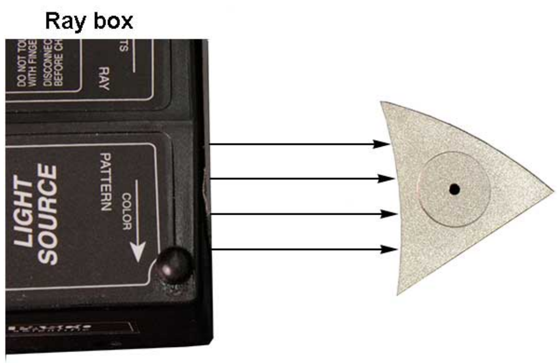
3. By turning the mirror piece, vary the angle of incidence while observing how the angle of reflection changes. What is the relation between the angle of incidence and the angle of reflection?

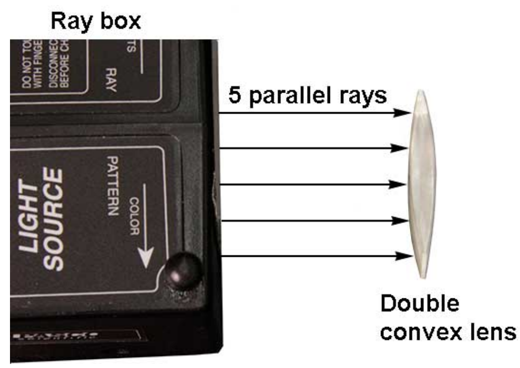
Relation:

____

PROCEDURE PART 3: CONVERGENCE AND DIVERGENCE OF RAYS

1. Either a mirror or a lens can converge or diverge parallel rays. The triangular mirror piece has a concave and a convex side, and there is a section of a double convex lens and a double concave lens. Adjust the ray box so that it makes five parallel white rays.

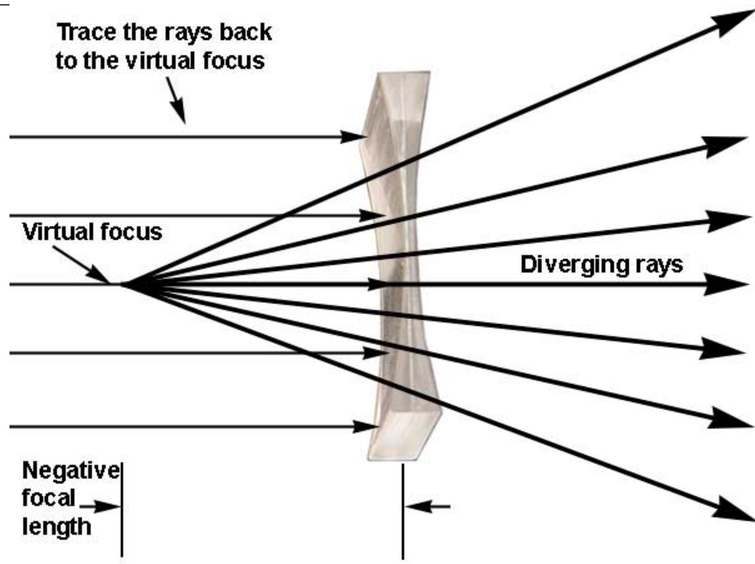




2. The concave mirror and the double convex lens (shown above) both converge the parallel rays to an approximate *focal point.* The distance between the lens or mirror surface and the focal point of parallel rays is the *focal length* of the mirror or lens. Measure the focal lengths of the concave mirror and convex lens in centimeters, and enter them in the table below.

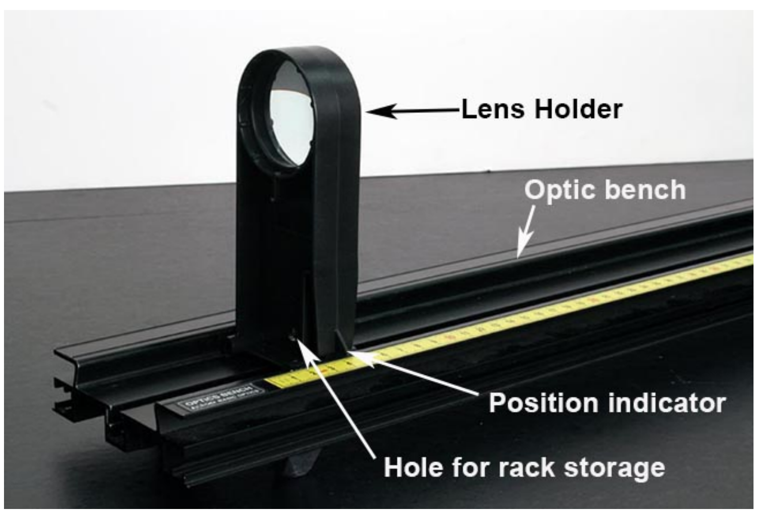
	A	B
1	Optical element	Focal Length
2	Concave mirror	
3	Double convex lens	
4	Convex mirror	
5	Double concave lens	

3. The convex mirror and the double concave lens both diverge the parallel rays. They have negative focal lengths, and the magnitude of the focal length is equal to the distance between the optical element and the point from which the rays appear to diverge. Using the convex mirror and the double concave lens (one at a time), sketch the mirror or lens surface in position, and trace the diverging rays on the white paper. Remove the mirror or lens, and continue tracing the rays back to the *virtual focus* using a ruler. Enter the (negative) focal lengths (in centimeters) of these optical elements in the table above.



PROCEDURE PART 4: IMAGE FORMATION AND FOCAL LENGTH OF A LENS

1. Place the 200-mm lens and the screen on the optical-bench track. Do not put the light source on yet.



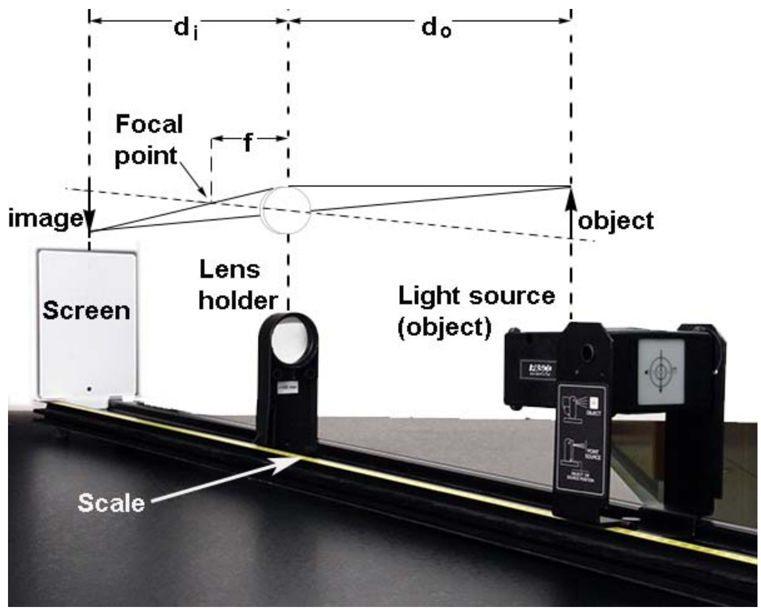
2. Focus a distant light source (such as a window, the trees outside the window, or a light at the other end of the room) on the screen. A distant source is effectively at infinity, the rays from the source are parallel, and the lens converges the rays to an image at the focal point. Measure the distance between the lens and the screen, and compare this distance to the stated focal length. (You may read positions off the optical bench scale and subtract them to find distances.)

   Notice that the image is inverted. This is similar to how your eye lens forms an inverted image of the outside world on your retina.

3. Now mount the light source with the circles and arrows side facing the lens and screen. You need to unplug the power cord of the light box, and then replug it when the box is mounted. (There are two ways to mount the light source in the bracket. Notice the two holes in the bracket for the detent buttons on either side. For one way, the offset of the bracket arm below permits reading the position of the light source directly from the scale; for the other way, you would need to correct for the setback of the light source.)

4. Adjust the position of the lens until the image of the light source is focused sharply on the screen. Read the distances d_o and d_i in the figure off the scale, and calculate the focal length of the lens from the thin-lens equation:

$$1/f = 1/d_\mathrm{o} + 1/d_\mathrm{i}. \tag{7}$$



Enter the data below:

d_o = ____

d_i = ____

$1/f$ = ____

f (calculated) = ______________________________

f (theoretical) = ______________________________

Here f (calculated) is the value obtained from the thin-lens equation, and f (theoretical) is the value read off the lens. These two focal lengths should, of course, agree approximately.

PROCEDURE PART 5: TWO-LENS SYSTEMS

1. Place the light source at 110 cm and the screen at 60 cm on the optical-bench scale. Place the +100 mm lens between the light source and the screen. You will find it possible to obtain a sharp image on the screen with the lens at about 72 cm. Is the image upright or inverted? Adjust for the exact focus, measure the object and image distances (read positions off the scale and subtract them), and compare the theoretical focal length with that obtained from the thin-lens equation.

   d_o = ____

   d_i = ____

   $1/f$ = ____

   f (calculated) = ______________________________

   f (theoretical) = ______________________________

   Is the image upright or inverted? ______________________________

2. The image formed at 60 cm can serve as the object for a second lens. Move the screen back, and place the +25 mm lens at 55 cm on the scale. Where does the image focus? Is it upright or inverted? Measure the object and image distances for the +25 mm lens, and compare the theoretical focal length with that obtained from the thin-lens equation.

   d_o = ____

   d_i = ____

   $1/f$ = ____

   f (calculated) = ______________________________

   f (theoretical) = ______________________________

   Is the image upright or inverted? ______________________________

3. If a second lens is placed <u>inside</u> the focal point of the first lens, the image of the first lens serves as a *virtual object* for the second lens. Place the +200 mm lens at 68 cm on the scale. The object distance is the negative of the distance between the lens and the point at which the image would have formed: namely, −8.0 cm if the first image were at 60 cm and the second lens were at 68 cm. Where does the image focus now? Is it upright or inverted? Compare the theoretical focal length with that obtained from the thin-lens equation.

   d_o = ____

   d_i = ____

   $1/f$ = ____

f (calculated) = ______________________________

f (theoretical) = ______________________________

Is the image upright or inverted? ______________________________

4. Repeat step 3, placing the diverging −25 mm lens at 68 cm on the scale. This strongly diverging lens bends the rays from the +100 mm lens outward so that they diverge and never come to a focus beyond the lens. Instead, look through the two lenses back to the source. You will see the virtual image at a distance. Is it upright or inverted? Calculate the image distance of the −25 mm lens with its virtual object. The result comes out negative. Look through the lenses again. Does the image distance seem reasonable?

   d_o = ____

   d_i = ____

   Does image distance seem reasonable? ______________________________

   Is the image upright or inverted? ______________________________

PROCEDURE PART 6: SIMPLE TELESCOPES

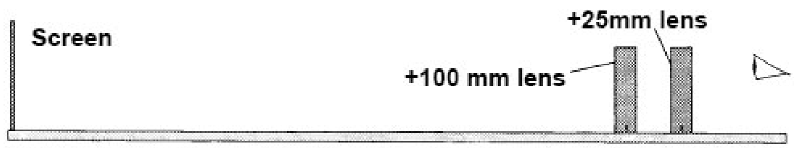
1. You have four lenses in holders; the lenses have focal lengths of +200 mm, +100 mm, +25 mm, and −25 mm. Carry these lenses over to a window so that you can look out at distant objects (such as a building across the quadrangle). DO NOT LOOK AT THE SUN WITH YOUR TELESCOPE ARRANGEMENTS. PERMANENT EYE DAMAGE MAY RESULT. To make a telescope, hold one of the short focal-length lenses near your eye and one of the longer focal-length lenses out with your arm, so that you look through both lenses in series. Adjust the position of the second lens (the objective) until a distant object is focused. The lens nearest your eye is called the *eye lens*, and the one farther out is called the *objective*.

2. <u>Galilean telescope</u>: Use the negative focal-length lens ($f = -25$ mm) as the eye lens and the +100 mm or +200 mm lens as the objective, and focus a distant object. Notice that the field of view is small and the image is distorted. Nevertheless, Galilei used an optical arrangement similar to this to discover the moons of Jupiter, the phases of Venus, sunspots, and many other heavenly wonders.

3. <u>Astronomical telescope</u>: Use the +25 mm lens as the eye lens and the +100 mm or +200 mm lens as the objective, and focus a distant object. Notice that the field of view is now larger and the image is sharper, although the image is inverted. You can also try the +100 mm lens as the eye lens and the +200 mm lens as the objective.

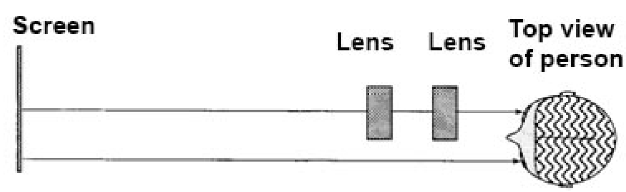
PROCEDURE PART 7: MEASURING THE POWER OF AN ASTRONOMICAL TELESCOPE

1. Use the +25 mm lens as the eye lens and the +100 mm lens as the objective. Place the lenses near one end of the optical bench and the screen at the other end, as shown below. Tape a piece of graph paper to the screen. (Graph paper and tape are in the lab room.)



2. Look through the eye lens, and focus the image of the graph paper by moving the objective.

3. (This procedure is a bit complex. Try your best and do not waste a lot of time on it.) Eliminate parallax by moving the eye lens until the image is in the same plane as the object (the screen). To observe the parallax, open both eyes and look through the lens at the image with one eye, while looking around the edge of the lens directly at the object with the other eye. Refer to the figures below. The lines of the image (solid lines in the figure below) will be superimposed on the lines of the object (dotted lines in the figure below). Move your head back and forth, and up and down. As you move your head, the lines of the image will move relative to the lines of the object due to parallax. To eliminate parallax, adjust the eye lens until the image lines do not move relative to the object lines when you move your head. When there is no parallax, the lines in the center of the lens appear to be stuck to the object lines. (Even when there is no parallax, the lines may appear to move near the edge of the lens because of lens aberrations.)



4. Measure the magnification of this telescope by counting the number of squares in the object that lie along a side of one square of the image. To do this, you must view the image through the telescope with one eye, while looking directly at the object with the other eye. Record the observed magnification in step 5.

5. The theoretical magnification for objects at infinity is equal to the ratio of the focal lengths. Record and compare the theoretical and observed magnifications below.

   Observed magnification = ______________________________

   Theoretical magnification = ______________________________

ADDITIONAL CREDIT PART 1: MEASURING A GLASSES PRESCRIPTION (3 mills)

The inverse of the focal length of a lens, $P = 1/f$, is called the *power* of the lens. The units of power are inverse meters which are renamed *diopters*, a unit commonly used by optometrists and opticians. The larger the power, the more strongly the lens converges rays. You can show that when two thin lenses are placed close together (so that the distance between them is much less than the focal lengths), the power P_T of the combined lenses is the sum of the powers P_1 and P_2 of the individual lenses:

$$P_\mathrm{T} = P_1 + P_2 \tag{8}$$

or

$$1/f_\mathrm{T} = 1/f_1 + 1/f_2. \tag{9}$$

The closest distance at which you can focus your eyes clearly (when you are exerting maximum muscle tension on your eye lens) is called your *near point*. The farthest distance at which you can focus your eyes clearly (when your focusing muscles are relaxed) is called your *far point*. Ideally, your far point is at infinity, and your near point is at least as small as 25 cm so you can read easily. If you are nearsighted, then your far point is at some finite distance; you cannot focus distant objects clearly. If you are farsighted, then your far point is "beyond infinity", so to speak, so that you need to exert eye-lens muscle tension even to focus distant objects. As you grow older, your *power of accommodation* (i.e., your ability to change the focal length of your eye lens) weakens and your near point moves out, so that you must have corrective lenses to focus on close objects, such as for reading. Thus, you notice older persons wearing reading glasses.

You may be wearing glasses, contact lenses, or have had laser eye surgery to correct your vision — or you may be lucky and have "perfect" vision without correction. In any case, use a meter stick (or other ruler) and the card with fine print to measure your near point (with correction, if any) as in the illustration below. The purpose of laying the meter stick on the table is to avoid poking it toward your eye.

Move the card in to the closest distance that you can focus clearly.

Near-point distance (corrected) = ______________________________

If you are nearsighted and wearing glasses, take off your glasses and measure your far point. (If you are wearing contacts, you may remove a contact and try this, but the step is optional.)

Far-point distance (uncorrected) = ______________________________

If you or your lab partner are nearsighted and wearing glasses, determine your glasses prescription as instructed below. If neither you nor your partner is nearsighted and wearing glasses, use the (uncorrected) data for Dr. Art Huffman: far point = 20 cm, near point = 18 cm. (Yes, his vision is that bad!)

If the eye is nearsighted, we want to put a diverging lens in front of it, which will shift the uncorrected far point to infinity. We can use the formula above to find the focal length of the glasses-eye combination. Let the (uncorrected) far-point distance be d, the eye-to-retina distance be i, the focal length of the eye lens while relaxed be f_{f}, and the focal length of the glasses be f_{g}:

$$\text{Without glasses:}\quad 1/d + 1/i = 1/f_{\mathrm{f}} \tag{10}$$

$$\text{With glasses:}\quad 1/\infty + 1/i = 1/f_{\mathrm{f}} + 1/f_{\mathrm{g}}. \tag{11}$$

Subtracting the first equation from the second gives the power P_{g} of the glasses:

$$P_{\mathrm{g}} = 1/f_{\mathrm{g}} = -1/d. \tag{12}$$

Compute your glasses prescription (or Art's) in diopters:

____

ADDITIONAL CREDIT PART 2: MEASURING THE FOCAL LENGTH OF A DIVERGING LENS (2 mills)

Devise a way, using your optical bench, to measure the focal length of a diverging lens. Then measure the focal length of your glasses as in Additional Credit Part 1, or measure the focal length of one of the unknown lenses supplied in the lab.

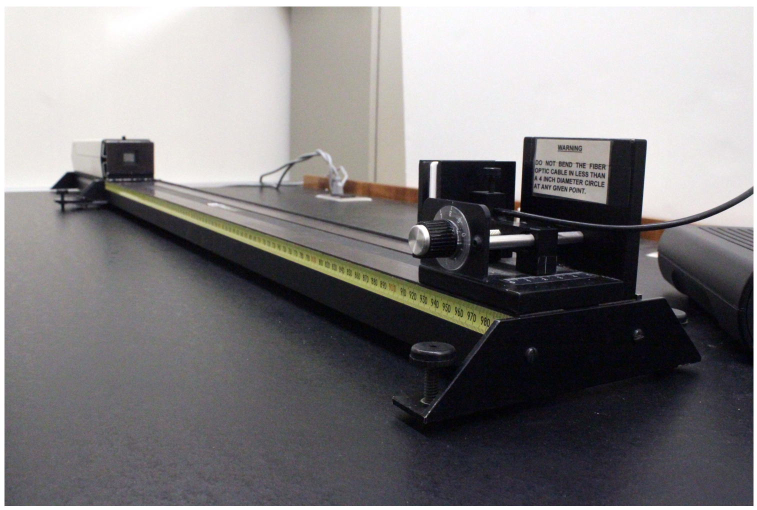
Sketch your plan for measuring the focal length of a diverging lens below, and report the measured <u>power</u> of the glasses or of the unknown lens.

Physical Optics

APPARATUS

Shown in the picture below:

- Optics bench with laser alignment bench and component carriers
- Laser
- Linear translator with photometer apertures slide and fiber optic cable



Not shown in the picture above:

- Computer with ScienceWorkshop interface
- High sensitivity light sensor with extension cable
- Slit slides and polarizers
- Incandescent light source
- Tensor Lamp

INTRODUCTION

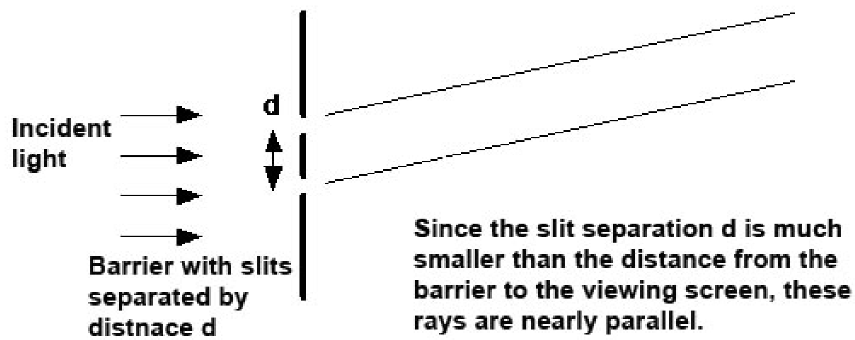
The objective of this experiment is to familiarize the student with some of the amazing characteristics of a laser, such as its coherence and small beam divergence. The laser will be used to investigate single- and double-slit diffraction and interference, as well as polarization. Furthermore, several interesting diffraction phenomena that are hard to see with standard light sources can be observed easily with the laser.

<u>WARNING: Do not look directly into the laser beam!</u> Permanent eye damage (a burned spot on the retina) may occur from exposure to the direct or reflected beam. The beam can be viewed without any concern when it is scattered from a diffuse surface such as a piece of paper. The laser beam is completely harmless to any piece of clothing or to any part of the body except the eye.

It is a wise precaution to keep your head well above the laser-beam height at all times to avoid accidental exposure to your own or your fellow students' beams. Do not insert any reflective surface into the beam except as directed in the instructions or as authorized by your TA. The laser contains a high-voltage power supply. Caution must be used if an opening is found in the case to avoid contacting the high voltage. Report any problems to your TA.

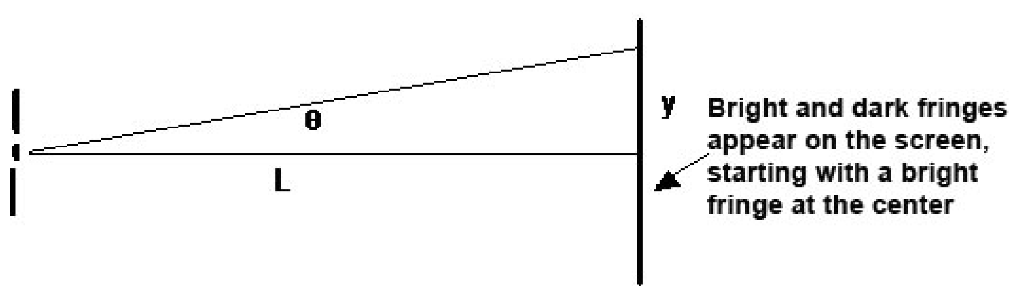
DOUBLE-SLIT INTERFERENCE

In the first part of the experiment, we will measure the positions of the double-slit interference minima. Schematically, a double-slit setup looks as follows:

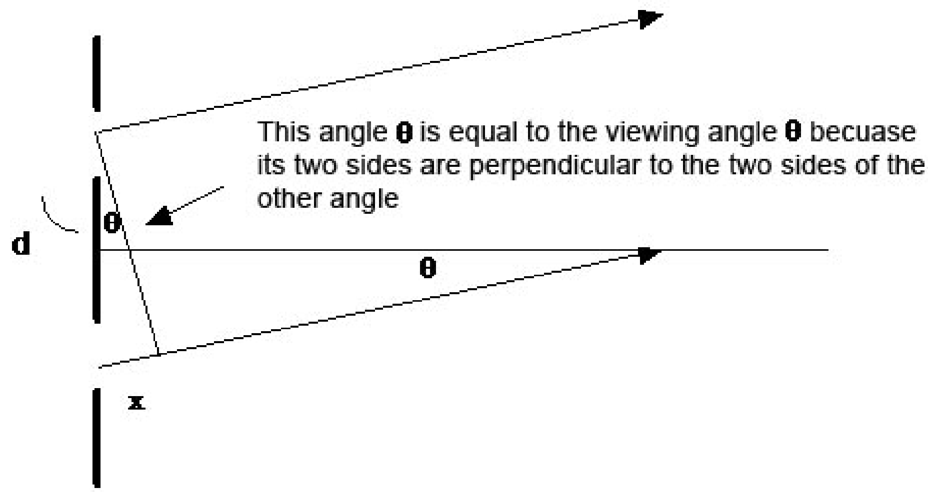


The incident laser light shining on the slits is *coherent*: at each slit, the light ray starts with the same phase. To reach the same point on the viewing screen, one ray needs to travel slightly farther than the other ray, and therefore becomes out of phase with the other ray. If one ray travels a distance equal to one-half wavelength farther than the other way, then the two rays will be 180° out of phase and cancel each other, resulting in destructive interference. No light reaches this point on the screen. At the center of the screen, the two rays travel exactly the same distance and therefore interfere constructively, producing a bright fringe. At a certain distance from the center of the screen, the rays will be one-half wavelength (or 180°) out of phase with each other and interfere destructively, producing a dark fringe. A bit farther along the screen, the rays will be one whole wavelength (or 360°) out of phase with each other and interfere constructively again. Farther still, the ways will be one and one-half wavelengths (or 360° + 180° = 540°) out of phase with each other and interfere destructively. Thus, the interference pattern contains a series of bright and dark fringes on the screen.

Let θ be the viewing angle from the perpendicular, as shown in the figure below:



Study the construction in Figure 3.



The small extra distance x that the lower ray needs to travel is $d\sin\theta$. If this distance is equal to an odd multiple of one-half wavelength, then the two rays will interfere destructively, and no light will reach this point on the screen:

$$\begin{aligned} &\text{interference minima at} \\ &d\sin\theta = N(\lambda/2) \\ &\text{for } N = 1, 3, 5, \ldots \end{aligned} \tag{1}$$

(An even value of N would separate the two rays by a whole number of wavelengths, causing them to interfere constructively.) Now, note that the expression $N = 2(n + 1/2)$ reproduces the odd numbers $N = 1, 3, 5, \ldots$ for $n = 0, 1, 2, \ldots$, so we can rewrite Eq. 1 as:

$$\begin{aligned} &\text{interference minima at} \\ &d\sin\theta = (n + 1/2)\lambda \\ &\text{for } n = 0, 1, 2, \ldots. \end{aligned} \tag{2}$$

Look at Figure 2 again. If y is the linear distance from the center of the pattern on the screen to the point of interference, and if the angle θ is small, then $\sin\theta \approx \tan\theta = y/L$. Thus, the positions of the minima are given by

$$y_n = (n + 1/2)\lambda L/d \quad \text{for } n = 0, 1, 2, \ldots, \tag{3}$$

and the distance between successive minima is

$$\Delta y = (y_{n+1} - y_n) = \lambda L/d. \tag{4}$$

The first part of this experiment involves measuring the positions of the interference minima and determining the wavelength of the laser light.

SINGLE-SLIT DIFFRACTION

When light passes through a single slit of non-zero width, rays from the different parts of the slit interfere with one another and produce another type of interference pattern. This type of interference — in which rays from many infinitesimally close points combine with one another — is called *diffraction*. We will measure the actual intensity curve of a diffraction pattern.

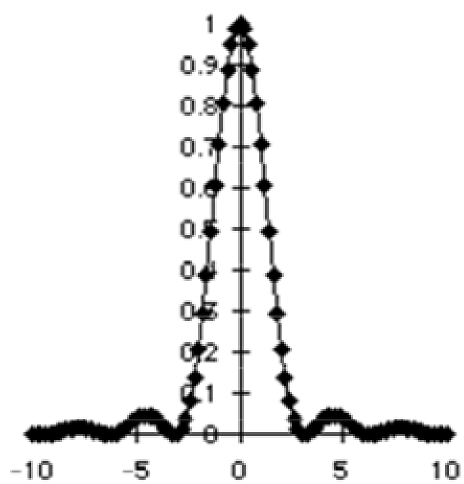
The textbook or the appendix to this experiment gives the derivation of the intensity curve of the diffraction pattern for a single slit:

$$I = I_0[(\sin\alpha)/\alpha]^2, \tag{5}$$

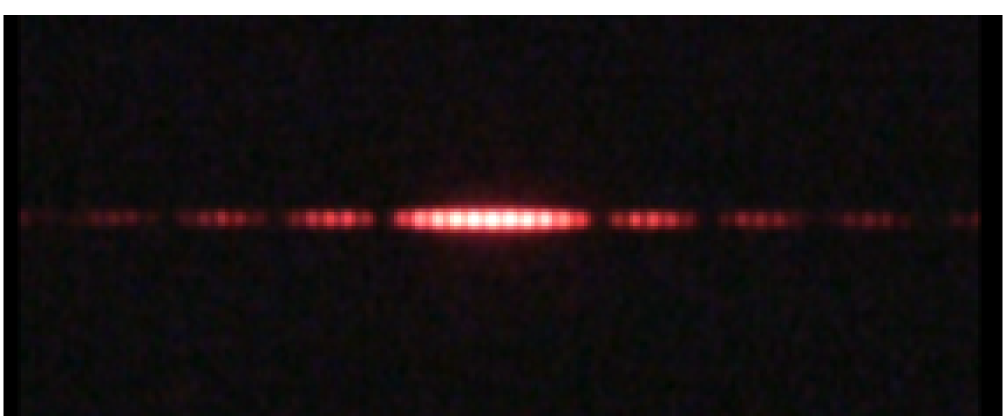
where

$$\alpha = \pi a \sin\theta/\lambda, \tag{6}$$

a is the slit width, and θ is the viewing angle. Here is a plot of the intensity I from Excel:



The image below demonstrates the intensity pattern; it shows the broad central maximum and much dimmer side fringes.



Let us locate the minima of the single-slit diffraction pattern. From Eq. 5, the minima occur where $\sin\alpha = 0$, except where α itself is zero. When α is zero, $\sin\alpha = 0$, and the expression 0/0 is indeterminate. L'Hopital's rule resolves this ambiguity to show that $\sin\alpha/\alpha \to 1$ as $\alpha \to 0$. Thus, $\alpha = 0$ corresponds to the center of the pattern and is called the central maximum. Elsewhere, the denominator is never zero, and the minima are located at the positions $\sin\alpha = 0$ or $\alpha = n\pi$, with $n =$ any integer <u>except</u> 0. From Eq. 6, we find that:

$$\begin{gathered}\text{diffraction minima at}\\ a\sin\theta = n\lambda\\ \text{for } n = \text{any integer } \underline{\text{except}}\ 0.\end{gathered} \tag{7}$$

Note that the central maximum is twice as wide as the side fringes. The centers of the side fringes are located approximately (but not exactly) halfway between the minima where $\sin\alpha$ is either $+1$ or -1, or $\alpha = (n + 1/2)\pi$, with $n =$ any integer <u>except</u> 0:

$$\begin{gathered}\text{diffraction maxima approx. at}\\ a\sin\theta = (n+1/2)\lambda\\ \text{for } n = \text{any integer } \underline{\text{except}}\ 0.\end{gathered} \tag{8}$$

(The maxima are only approximately at these positions because the denominator of Eq. 5 depends on α. To find the exact positions of the maxima, we need to take the derivative of I with respect to α and set it equal to zero, then solve for α.)

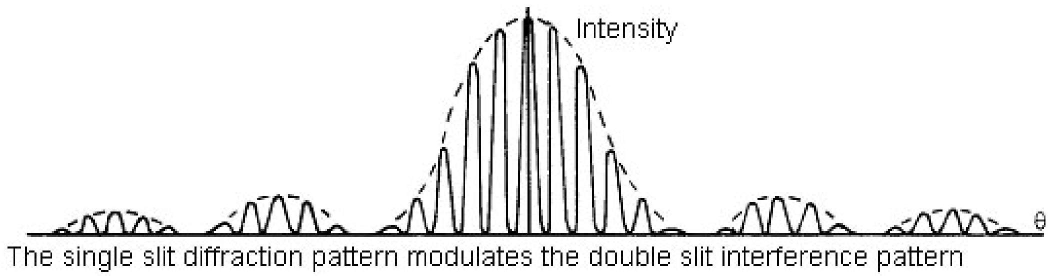
As mentioned above, the side fringes are much dimmer than the central maximum. We can estimate the brightness of the first side fringe by substituting its approximate position $\alpha = 3\pi/2$ into Eq. 5:

$$I(\text{first side fringe})/I_0 = 1/(3\pi/2)^2 = 0.045. \tag{9}$$

The first side fringe is only 4.5% as bright as the central maximum.

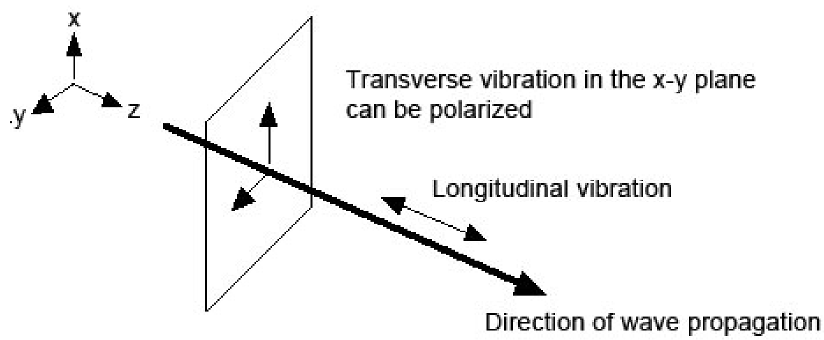
Note an important point about diffraction: As the single slit is made more narrow, the central maximum (and indeed the entire pattern) spreads out. We can see this most directly from the position of the first minimum in Eq. 7: $\sin\theta_1 = \lambda/a$. As we try to "squeeze down" the light, it spreads out instead.

Consider the double-slit interference setup again. Eq. 3 shows that the fringes are equally spaced for small viewing angles, but we now wish to determine the brightness of the fringes. If the two slits were very narrow — say, much less than a wavelength of light ($a \ll \lambda$) — then the central maxima of their diffraction patterns would spread out in the entire forward direction. The interference fringes would be illuminated equally. But we cannot make the slits too narrow, as insufficient light would pass through them for us to see the fringes clearly. The slits must be of non-zero width. Their central diffraction maxima will nearly overlap and illuminate the central area of the interference fringes prominently, while the side fringes of the diffraction pattern will illuminate the interference fringes farther from the center. A typical example is shown below.



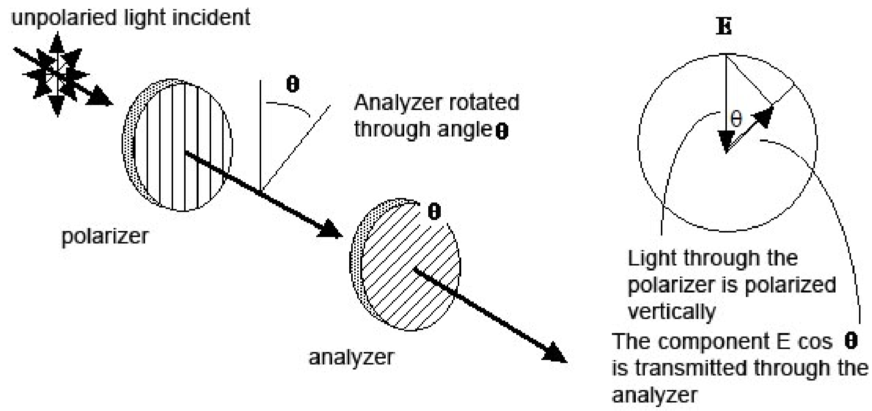
POLARIZATION

Consider a general wave moving in the z direction. Whatever is vibrating could be oscillating in the x, y, or z directions, or in some combination of the three directions. If the vibration is along the direction of wave motion (i.e., in the z direction), then the wave is said to be longitudinal. Sound is a *longitudinal* wave of alternate compressions and rarefactions of air. If the vibration is perpendicular to the direction of wave motion (i.e., in the xy plane), then the wave is said to be transverse. (Certain kinds of waves are neither purely longitudinal nor transverse.) Since one particular direction within the xy plane can be selected, a transverse wave can be *polarized*.



The simple fact that light can be polarized tells us that light is a transverse wave. According to Maxwell's equations, light is electromagnetic radiation. The electric and magnetic field vectors oscillate at right angles to each other and to the direction of wave propagation. We assign the direction in which the electric field oscillates as the polarization direction of light. The light from typical sources such as the Sun and light bulbs is *unpolarized*; it is emitted from many different atoms vibrating in random directions. A simple way to obtain polarized light is to filter unpolarized light through a sheet of Polaroid. Such a sheet contains long, asymmetrical molecules which have been cleverly arranged so that the axes of all molecules are parallel and lie in the plane of the sheet. The long Polaroid molecules in the sheet are all oriented in the same direction. Only the component of the incident electric field perpendicular to the axes of the molecules is transmitted; the component of the incident electric field parallel to the axes of the molecules is absorbed.

Consider an arrangement of two consecutive Polaroid sheets:



The first sheet is called the *polarizer*, and the second one is called the *analyzer*. If the axes of the polarizer and analyzer are crossed (i.e., at right angles to each other), then no light passes through the sheets. (Real polarizers are not 100% efficient, so we might not see exactly zero light.) If the axis of the analyzer were aligned parallel to that of the polarizer, then 100% of the light passing the polarizer would be transmitted through the analyzer. The diagram above shows that if the analyzer is oriented at an angle θ with respect to the polarizer, then a component of the incident electric field $E\cos\theta$ will be transmitted. Since the intensity of a wave is proportional to the square of its amplitude, the intensity of light transmitted through two polarizers at an angle θ with respect to each other is proportional to $\cos^2\theta$. This result is called *Malus' Law*, which we will test in this experiment.

An interesting situation arises if a third polarizer is inserted between two crossed polarizers. No light passes through the crossed polarizers initially, but when the third polarizer is added, light is able to pass through when the third polarizer has certain orientations. How can the third polarizer, which can only absorb light, cause some light to pass through the crossed sheets?

EQUIPMENT

At your lab station is an optics bench. A laser is located at one end of the bench, on a laser alignment bench, while a linear translator with a dial knob that moves the carriage crossways on the bench can be found at the other end. Between the laser and the linear translator are one or more movable component carriers. Fitted into a small hole in the linear translator is a fiber-optic probe connected to a high-sensitivity light sensor which, in turn, is connected by an extension cable to the ScienceWorkshop interface. Be careful with the probe. Do not bend the probe in a circle of less than 10-cm diameter at any given point. Also, do not bend the probe within 8 cm of either end. A slit of width 0.2 mm has been placed just in front of the probe to provide 0.2-mm resolution. (Note: Do not remove the Photometer Apertures slide from the translator and use it as a single slit.)

Light from the laser is transmitted through the probe to the high sensitivity light sensor, which provides an intensity reading. The linear translator (which is basically a carriage mounted on a threaded rod) moves the probe along the axis of the rod. An intensity plot of the pattern produced by a slit placed between the light source and the probe can be made by scanning the probe along the axis of the rod and taking readings from the high sensitivity light sensor.

The probe can be attached to the high sensitivity light sensor by slipping the optic output connector (BNC plug) of the probe over the input jack on the high sensitivity light sensor. A quarter-twist clockwise locks the probe to the high sensitivity light sensor; push the connector towards the sensor box and a quarter-twist counterclockwise disengages it.

The probe attenuates the light intensity reaching the selenium cell to approximately 6.5% of its value when the probe is not used. This makes measurements of absolute intensity impossible. However, for these experiments, only the relative intensities are needed.

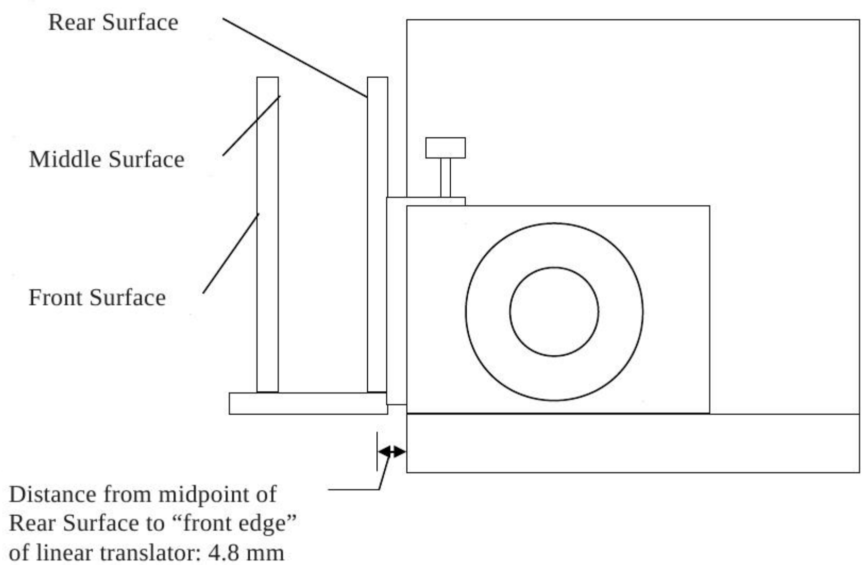
PROCEDURE PART 1: DOUBLE-SLIT INTERFERENCE

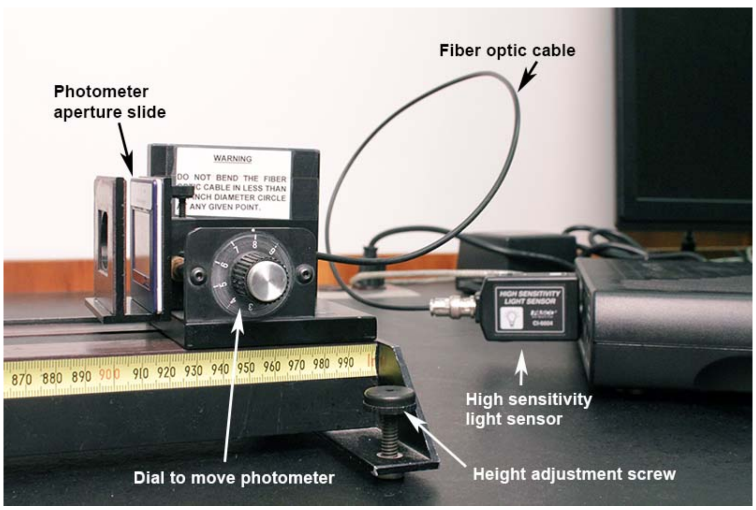
In this part of the experiment, we will locate only the minima of the interference pattern and measure the distance between them.

1. Open PASCO Capstone and choose the "Graph & Digits" option. Click the Hardware Setup tab to display the interface. Click on channel "A" and select "Light Sensor". In the digits display box, click on "Select Measurement" and choose "Light Intensity". Click "Record" to test out the sensor.

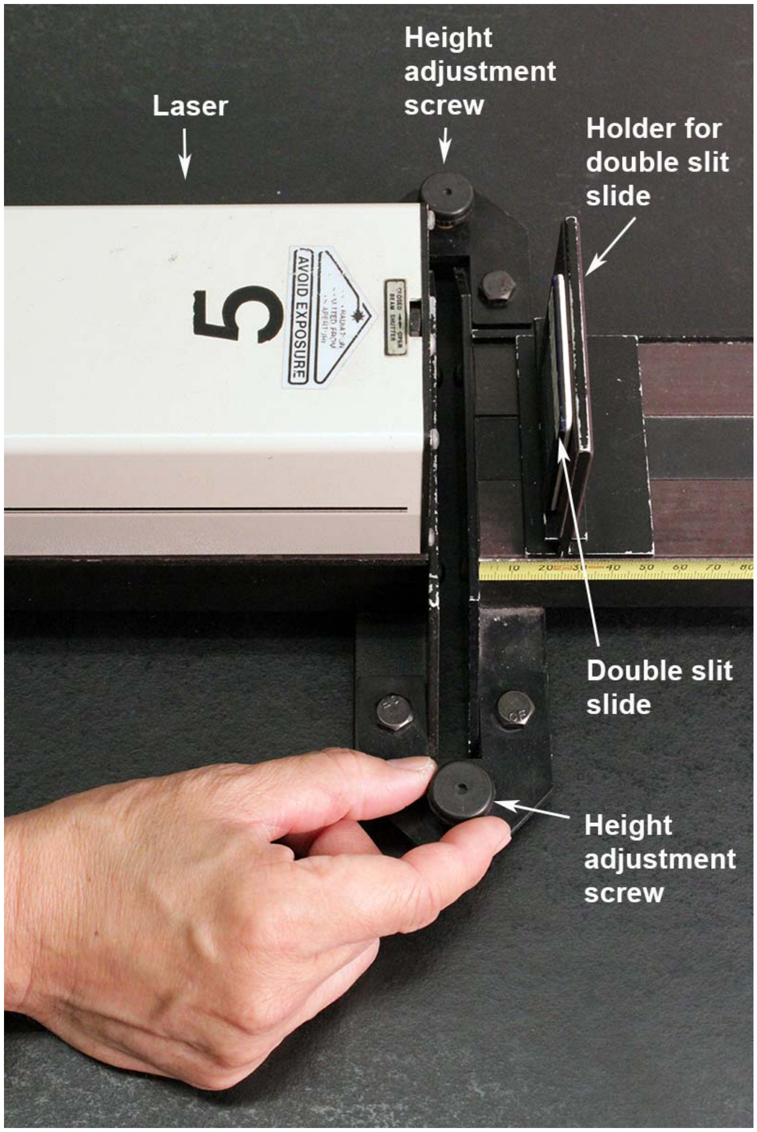
2. Look at the component carrier. A white line on the side of the carrier indicates the carrier position with reference to the meter scale on the optics bench. The white line is in the middle of the two vertical surfaces.

3. Study the translator carriage for a moment. At the back, a pointer line rides over a scale graduated in millimeters. One turn of the dial moves the pointer 1 millimeter, so the dial is reading in tenths of a millimeter. You can probably estimate hundredths of a millimeter on the dial scale. To begin aligning the system, move the translator carriage so the pointer is around the midpoint (approximately 24 mm) of the scale. Note there are three surfaces to which you can attach slides (see figure and image below). When using the Photometer Apertures slide, put it on the Rear Surface only, closest to the fiber optic cable. Also note there isn't a white line to indicate the linear translator position with reference to the meter scale on the optics bench. Using the "front edge" of the translator as the indicator, the middle of the Rear Surface is offset by 4.8 mm.



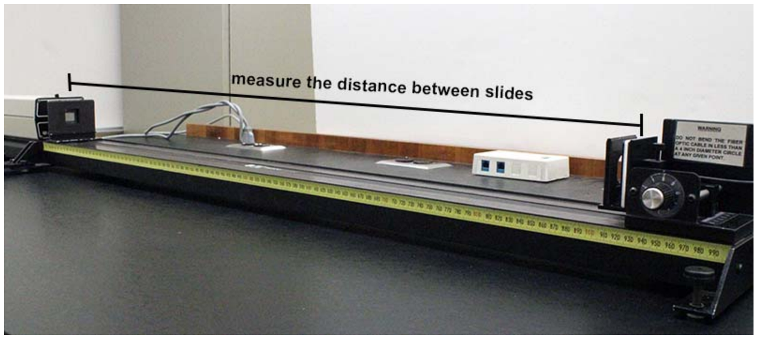


4. Start aligning the laser. Remove all slides (which attach magnetically to the carriers and the rear surface of the translator carriage) from the optics-bench setup. Turn on the laser and align the beam so it hits the center of the fiber-optic cable end. You can do this by adjusting the laser alignment bench screw at the back of the laser to set the beam at the right level so that when the translator carriage is moved by turning its dial, the end of the fiberoptic cable moves across the center of the laser beam.

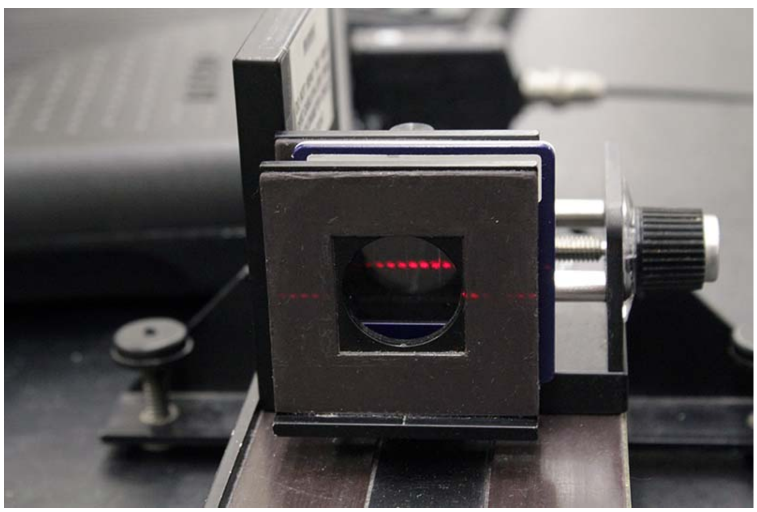


Be careful not to bump the laser, laser alignment bench, or optics bench when you are working later on the experiment so as to disturb the alignment. This is an easy mistake to make, especially with more than one person working on the experiment!

5. Place the Photometer Apertures slide on the rear surface of the translator stage. This slide has four single slits, but do not confuse it with the slides with single and double slits whose patterns you will be measuring. Position the 0.2-mm slit in front of the fiber optic terminal so that the laser beam is centered on it, shining into the fiber-optic cable end. The smaller the aperture you use the more detail you can detect in the pattern; however, you are also allowing less light into the light sensor and may not be able to detect the dimmest parts of the pattern. We suggest you use the 0.2-mm aperture for the double- and single-slit measurements below, but feel free to try other apertures if you think they would improve the results.



6. Position the narrowest double slit on the component carrier close to the laser so that when the laser is turned on, the double-slit fringe pattern is thrown onto the aperture slide. Note the modulated form of the pattern. Either start recording data or use "Monitor Data". Change the "Gain" on the light sensor to get a value between 1 and 5 volts.



7. Carefully record in the "Data" section the positions of the slit slide and the aperture slide using the optical-bench scale. The difference between these two positions is the distance L in Figure 2 and Eq. 3.

8. As you turn the dial of the translator stage, the aperture will move across the pattern. Measure and record the distances between the minima for five successive fringes carefully. Average the five distances. The translator stage may have "backlash": when reversing its direction, you need to turn the dial a perceptible distance before the stage begins to move. Therefore, turn the dial in only one direction when making the actual measurements.

9. Using Eq. 4, calculate the wavelength of the laser light. Compare it with the actual wavelength of 632.8 nm, and calculate the percentage error. (This is an atomic transition in neon atoms.)

PROCEDURE PART 2: POLARIZATION

1. The laser is not useful for polarization experiments because the laser beam is already partially polarized and the plane of polarization is rotating with time. You can check this by placing a polarizer between the laser and the fiber optic probe, and observing the Capstone reading. Instead, set the "Gain" on the light sensor to "1". Remove all slides, including the apertures slide. Put the Incandescent Light Source on the optics bench so the end with the light coming out is about 50 cm from the linear translator. Turn on the light source and adjust the bulb to get a bright beam to fall on the fiber-optic probe end. Place a polarizer on one of the component carriers and one on the front surface of the translator carriage.

2. Note that the polarizers are graduated in degrees and you can read off the angle from the marker on the bottom of the component carrier. Set both angles to zero for full transmission. Click "Record" to monitor the light sensor output. Adjust the gain of the light sensor if necessary.

3. Take intensity readings for every $10°$ of rotation of one of the polarizers from $0°$ to $90°$.

4. Enter the angle and intensity data in two columns in Excel. In a third column, calculate $I_0 \cos\theta$. In a fourth column, calculate the theoretical intensity $I_0 \cos^2\theta$. Chart with Excel, and compare the experimental and theoretical curves. Is the cosine-squared curve clearly a better fit than the cosine curve? You may print out this Excel page for your records.

5. As a final polarization measurement, experiment with three polarizers. Record the data requested below in the "Data" section.

   a. Record the intensity of the light with no polarizers. You may have to change the gain on the sensor.

   b. Add one polarizer between the source and sensor, and record the intensity.

   c. Add a second polarizer, adjust for minimum intensity (crossed polarizers) and record the intensity.

   d. Now insert a third polarizer between the first two, and rotate it. For what angle of the middle polarizer (with respect to the first) does a maximum of light pass through all three polarizers?

   e. Record the intensity of light that passes through at the maximum position.

   f. Convert the measurement in step e to a decimal fraction of the total intensity (found in step a).

   g. What should the theoretical fraction be?

ADDITIONAL CREDIT PART 1: SINGLE SLIT (2 mills)

Measure the intensities of the side fringes, and compare them with the theoretical values.

1. Following the reasoning leading up to Eq. 8, calculate the intensity of the second side fringe as a decimal fraction of the intensity of the central maximum.

2. Set the "Gain" on the light sensor to "1", and remove the incandescent light source. Recheck the laser alignment as in step (4) of the double-slit procedure. Position the apertures slide on the 0.2-mm slit.

3. Insert a single slit on one of the component carriers. Check that you are obtaining a nice single-slit pattern as in Figure 4 or 5 across the apertures slide.

4. In the "Data" section table, record the intensity of the central maximum, as well as the intensity of the first and second side fringes, in one column. You can locate the maxima by rotating the translator-stage dial while observing the light sensor output. In the second column, convert the intensities to a decimal fraction of the intensity of the central maximum. Record the theoretical value next to the results of the fractional intensities of the side fringes.

ADDITIONAL CREDIT PART 2 (3 mills)

Measure a single-slit intensity curve, and compare it with the theoretical curve.

1. Call up Excel on your computer. Enter the column of distance measurements for every 0.2 mm by using a "Series" operation.

2. Set up the narrowest slit on the optical bench. Start at the center of the central maximum, and record intensity readings every 0.2 mm past the second minimum (so that you cover the first side fringe) in the next column of Excel.

3. You need the slit width to calculate the theoretical curve from Eqs. 4 and 5. Measure this width with the traveling microscope.

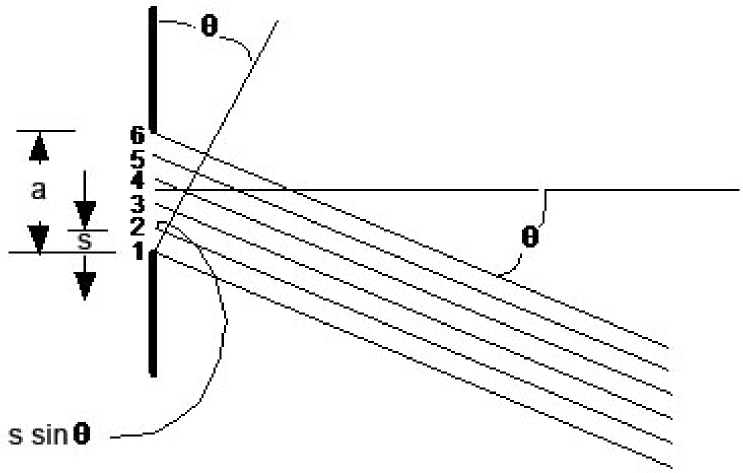
4. In the third column, compute the theoretical intensity from Eq. 4. Enter the formula correctly into the first cell; then use the "Fill Down" operation.

5. Graph your theoretical and experimental curves (normalized to the intensity at the center of the central maximum). If all looks well, you may print your chart out with the data to keep for your records.

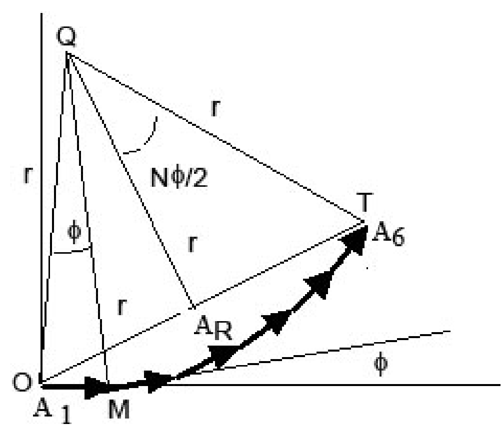
APPENDIX: SINGLE-SLIT THEORY CONTINUED

We will use a geometrical, or *phasor*, method to derive Eq. 5 for the intensity curve of the single-slit diffraction pattern.

Suppose that instead of a single beam of light passing through a slit of width a, there are N tiny sources of light (all monochromatic and coherent with each other) which are separated from each other by a distance s in such a way that $Ns = a$. We will start with six light sources so that our pictures are clear, but will eventually let N go to infinity.



In Figure 10, we are looking at the light rays coming from the sources that make an angle θ with the horizontal. Observing the figure closely, we see that the ray from source 2 travels a distance $s \sin\theta$ greater than the ray from source 1 en route to the viewing screen on the right (not shown in the figure). Thus, the light from a given source is out of phase with the light from the source just below it by a phase $(2\pi s \sin\theta)/\lambda$, which we denote ϕ for brevity. We will assign an amplitude A to each source and, with the phase difference ϕ, draw a diagram showing the addition of the light rays at some angle θ (Figure 11).



We see that each vector makes an angle ϕ (phase difference) with the preceding one, and the resultant vector is the total *amplitude* of light seen at angle θ. When we determine what OT $= A_{\mathrm{R}}$ is in terms of ϕ and A, we square the result to obtain the total *intensity* of light at angle θ.

Note that the vectors A_1 through A_6, each of equal magnitude A, lie on a circle whose radius is OQ $= r$. Since the angle OQM is ϕ, it follows that $A = \mid A_1 \mid = 2r\sin(\phi/2)$ (some steps have been skipped here). But angle OQT is $N\phi$ (where $N = 6$ in this case), so $A_{\mathrm{R}} = 2r\sin(N\phi/2)$. Solving for A_{R} in terms of A and ϕ, we find

$$A_{\mathrm{R}} = A\sin(N\phi/2)\,/sin(\phi/2). \tag{10}$$

This is the amplitude of light from N slits, where $N = 6$ for the case we are illustrating. We now wish to let N go to infinity. As N approaches infinity, s approaches 0, but Ns approaches a (the slit width). Thus, $N\phi$ approaches Φ, the total phase difference across the entire slit:

$$\Phi = (2\pi a/\lambda)\sin\theta. \tag{11}$$

Thus, Eq. 10 becomes

$$A_{\mathrm{R}} = A\sin(\Phi/2)/\sin(\Phi/2N). \tag{12}$$

The angle $\phi = \Phi/N$ becomes infinitesimally small, so we can replace the sine term in the denominator of Eq. 12 with the angle itself:

$$A_{\mathrm{R}} = A\sin(\Phi/2)/(\Phi/2N). \tag{13}$$

Finally, $NA = A_{\mathrm{T}}$ (the total amplitude of light from the slit), so

$$A_{\mathrm{R}} = A_{\mathrm{T}}\sin(\Phi/2)/(\Phi/2). \tag{14}$$

If we let $\alpha = \Phi/2 = (\pi a/\lambda)\sin\theta$, then

$$A_{\mathrm{R}} = A_{\mathrm{T}}(\sin\alpha/\alpha). \tag{15}$$

The intensity is proportional to the square of the amplitude, so

$$I = I_0[(\sin\alpha)/\alpha]^2. \tag{16}$$

This is Eq. 5.

DATA

Procedure Part 1:

5. Slit-slide position = ______________________________

   Aperture-slide position = ______________________________

   L = ______________________________

6. Positions of 5 minima = ______________________________

   ____

   ____

   ____

   ____

   Average difference = ______________________________

7. Measured distance between inside edges = ______________________________

   Measured slit width = ______________________________

   d from measurements above = ______________________________

   Nominal d on slide = ______________________________

8. Calculated wavelength = ______________________________

   Percentage error = ______________________________

   Show your calculation of the wavelength neatly below.

Procedure Part 2:

3. You may pring out your data in Excel.

4. You may pring out your data in Excel.

5. a. Intensity with no polarizers = ______________________________

   b. Intensity with one polarizer = ______________________________

   c. Intensity with crossed polarizers = ______________________________

   d. Angle of middle polarizer = ______________________________

   e. Intensity with third polarizer = ______________________________

   f. Fraction = ______________________________

   g. Theoretical fraction = ______________________________

Additional Credit Part 1 Data:

	A	B	C	D
1	fringe	measured intensity	fractional intensity	theoretical intensity
2	central			
3	1st side			
4	2nd side			

Fluids and Thermodynamics

APPARATUS

Shown in the pictures below:

- Electric tea kettle for hot water
- Temperature sensor
- Copper can with attached tube and quick-disconnect
- Rubber bands or tape to tape temperature sensor to metal can
- Low-pressure sensor

Not shown in the pictures above:

- Computer and ScienceWorkshop interface
- Tall container with tubing and quick disconnector for pressure-versus-depth measurements
- Meter stick
- 1000-ml beaker
- Rectangular aluminum and brass blocks
- Spring scale
- Acculab digital scale
- Vernier calipers
- 50-, 100-, and 200-g masses
- Barometer in room
- Paper towels and/or sponges in room to clean up splashed water

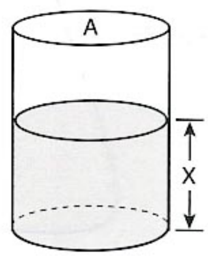
INTRODUCTION

In this experiment, you will measure the pressure of water as a function of depth, investigate the buoyant force exerted by water on submerged objects, and use ideal-gas-law properties of air to deduce and calculate the coldest possible temperature, called *absolute zero*. (More properly, one should say absolute zero is the lower limit of cold temperatures, since absolute zero can be approached but not reached.)

PASCAL'S LAW

Pressure, by definition, is force per unit area. In SI units, pressure is measured in Newtons per square meter, which is also called Pascals (Pa). Atmospheric pressure is approximately 100,000 Pa or 100 kilopascals (kPa). The pressure sensor used in this experiment reads in kPa.

To determine the variation of pressure with depth, consider a cylindrical slab of liquid of cross-sectional area A and height x.



(The slab need not be a circular cylinder; the cross-sectional area can have any shape as long as the sides are vertical.) We consider only the case in which the liquid is incompressible and has constant density ρ_l. The mass of liquid in the slab is equal to the density multiplied by the volume — $\rho_l Ax$ — while the weight of the liquid is $\rho_l gAx$. Thus, the pressure P exerted by the liquid on the bottom of the slab is equal to the weight divided by the area,

$$P = \rho_l gx, \tag{1}$$

and we see that the pressure is proportional to the depth x. This result is known as *Pascal's Law.*

ARCHIMEDES' PRINCIPLE

Archimedes' Principle tells us that an object completely or partially submerged in a fluid (liquid or gas) experiences an upward buoyant force. The buoyant force is equal in magnitude to the weight of the fluid displaced by the object. Suppose we place a rubber duck in a bathtub of water. The duck is less dense than the water, so it naturally floats. If we push down on the duck, though, we feel some "resistance" as the duck enters the water. This "resistance" is the upward buoyant force exerted by the water on the duck. We also observe that the duck sweeps aside — or displaces — a certain amount of water to make room for itself. When the duck is completely submerged in water, the displaced volume of water is equal to the total volume of the duck.

In general, to determine the magnitude of the buoyant force that a liquid exerts on a submerged object, we must consider how much of the object (of total volume V) lies below the liquid surface. Since only the submerged portion of the object displaces liquid, we see that the displaced volume of liquid is equal to the object's submerged volume. If we call the displaced volume V_d, then the mass of the displaced liquid is $\rho_\mathrm{l} V_\mathrm{d}$, and the weight of the displaced liquid is $\rho_\mathrm{l} g V_\mathrm{d}$. From Archimedes' Principle, the magnitude of the buoyant force B must be equal to this weight:

$$B = \rho_\mathrm{l} g V_\mathrm{d}. \tag{2}$$

For an object completely submerged in the liquid, $V_\mathrm{d} = V$. However, for an object only partially submerged, $V_\mathrm{d} < V$.

When an object suspended from a spring scale is lowered slowly into a liquid, the forces acting on the object are the (upward) spring force F_s, the (upward) buoyant force B, and the (downward) gravitational force or weight W. Since the object is essentially stationary, these three forces must balance:

$$\sum Fy = F_\mathrm{s} + B - W = 0. \tag{3}$$

Therefore, the reading of the spring scale is

$$F_\mathrm{s} = W - B. \tag{4}$$

This reading is known as the *apparent weight* of the object. Calling ρ_o the density of the object, we see that $W = mg = \rho_\mathrm{o} g V$. From this result and Eq. 2, it follows that

$$F_\mathrm{s} = \rho_\mathrm{o} g V - \rho_\mathrm{l} g V_\mathrm{d} = (\rho_\mathrm{o} V - \rho_\mathrm{l} V_\mathrm{d}) g. \tag{5}$$

THE IDEAL GAS LAW

Experimentally, it is found that any sufficiently rarefied gas satisfies the *ideal gas law*:

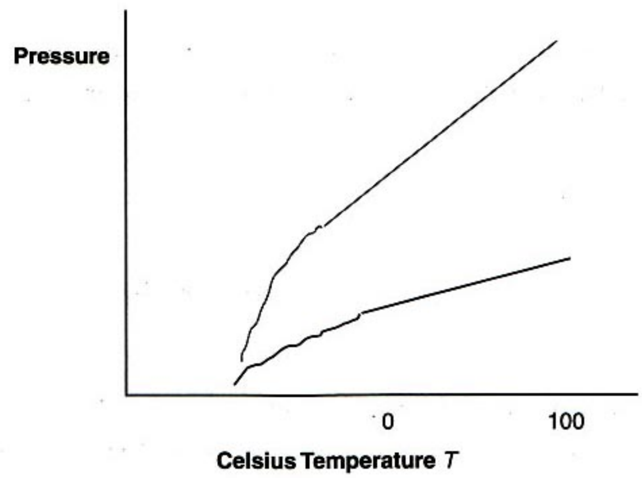
$$PV = nRT, \tag{6}$$

where P is the pressure, V is the volume, T is the absolute temperature, n is the number of moles of gas, and R is the universal gas constant (8.314 J/mol K). Historically, the different dependencies codified in this equation were named after the scientists who discovered them:

- Boyle's Law: P is inversely proportional to V (if T is held constant)
- Charles' Law: V is directly proportional to T (if P is held constant)
- Gay-Lussac's Law: P is directly proportional to T (if V is held constant)

MEASURING ABSOLUTE ZERO WITHOUT RISKING FROSTBITE

If we take different types of gases in various volumes — say, a liter of hydrogen, a cubic meter of helium, 500 cubic centimeters of air, a cubic centimeter of chlorine, etc. — and measure the dependencies of pressure P on Celsius temperature T at constant volume, we would obtain curves such as those shown below:



In each case, the pressure-versus-temperature relationship is linear at sufficiently high temperatures (i.e., the ideal-gas behavior); but as the temperature is reduced, each gas eventually deviates from the straight-line relationship. At sufficiently cold temperatures, the gas liquefies. However, the extrapolation of the linear part of the pressure-versus-temperature curve in each case intersects the temperature axis at the same point T_0 — the temperature we call *absolute zero* — irrespective of the type of gas or its initial pressure and volume.

Thus, we can take any gas (e.g., air), measure its pressure dependence on Celsius temperature at convenient values near room temperature, extrapolate the curve, and determine the value of absolute zero. For example, if we measure $P = mT + b$, where m is the slope of the P vs. T curve and b is the pressure at zero degrees Celsius, then the extrapolated intercept on the axis where $P = 0$ is the Celsius temperature of absolute zero:

$$T_0 = -b/m. \tag{7}$$

(If the chosen gas were very "non-ideal" at room temperature and atmospheric pressure, then we might need to reduce the pressure until its behavior approaches the ideal limit.) In this experiment, we will be using air at pressures near atmospheric and temperatures between the boiling and freezing points of water.

EQUIPMENT

In the first part of this experiment, pressure is measured by a small pressure sensor box which connects to one of the analog plugs of the Pasco interface. The sensor box sends a voltage proportional to the pressure toward the interface. The interface then converts the analog voltage to a digital signal and sends it to the computer. You can enter the pressure into tables, graph it, and so forth. The actual gas or liquid pressure is delivered to the pressure port of the sensor box by a plastic tube with a "quick-disconnector" piece which fits into the port.

Since you will now be dealing with water, be very careful not to get it on the computer, the keyboard, or the interface box. The tall container has two stopcocks; the lower one has a hose with a quick-disconnector on the end. Make sure both stopcocks are closed, and hook the quick-disconnector to the pressure sensor box. (The stopcocks are closed when their T-handles are turned perpendicular to the direction of liquid flow, and open when the T-handles are parallel to the liquid flow.) Place a plastic meter stick into the container so you can read the depth of water in centimeters.

INITIAL SETUP

1. Plug the cable from the pressure sensor box into analog channel A of the signal interface.
2. Turn on the signal interface and the computer.
3. Call up Capstone and choose the "Graph & Digits" option. In the "Hardware Setup" tab, click on channel A and select "Pressure Sensor, Low". A pressure sensor symbol appears under analog channel A.
4. In the digits box, click "Select Measurement" and choose "Pressure (kPa)".
5. Add some water to the tall container, and place the beaker to catch water from the upper stopcock. Use a small piece of hose from the upper stopcock to the beaker. The pressure of the full column will shoot water over the beaker if the upper stopcock is fully opened. The hose from the closed lower stopcock should be connected to the pressure sensor box.
6. Click the "Record" button, and check that you are obtaining gauge pressure readings. (The gauge pressure is the pressure exerted by the water, and is equal to the difference between the absolute and atmospheric pressures. Equivalently, it is equal to the pressure above atmospheric.) When you open the lower stopcock, the pressure increases. Although the trapped air in the tube should prevent any water from getting into the sensor, take caution not to disconnect the quick-disconnector from the pressure sensor before turning off the stopcock. Allow some water to drain out of the tall container into the beaker while observing the pressure reading. The reading should, of course, decrease as the water drains out. Stop recording and click "Delete Last Run" to discard this data set.

PROCEDURE PART 1: PRESSURE

1. Click on the table icon on the right side of the screen and drag a new table to your work space. Click "Select Measurement" on the first column of the table and choose "Pressure (kPa)". Click "Select Measurement" on the second column. In the "Create New" option, choose "User-Entered Data". You will be entering the water depth in this column. Feel free to Change the title of this column.

2. On the bottom of the screen, click "Continuous Mode" and change this to "Keep Mode".

3. Pour water into the container until it is about 75 cm deep. Note that the stopcock to the pressure sensor is 3 cm from the bottom, so you need to subtract 3 cm from all of the meterstick-level readings. Be sure to convert the level readings to meters before typing them in. Open the stopcock to the pressure sensor.

4. Click "Preview" to initiate the sensor. Then click "Keep Sample" to have the pressure reading added to the table. Enter the depth reading in meters (3 cm less than the meterstick reading) in the second column of your table. Take pressure readings at each of the following marks on the meter stick: 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, and 20 cm.

5. For the final entry, type in zero for the depth. Close the lower stopcock, disconnect the hose from the sensor, and click "Keep Sample" to record the gauge pressure of the atmosphere (which should be zero). Again, the stopcocks are open when their T-shaped tops are aligned with their tubes, and closed otherwise. Click the "Stop" button to end the data run.

6. Click the "Select Measurement" botton on the y-axis and choose "Pressure (kPa)" and put your depth recordings on the y-axis. Click the "Apply Selected curve fits..." tool and select "Linear". A box should appear that tells you the slope and y-intercept of the best-fit line. According to the equation of pressure versus depth ($P = \rho_l g x$), the slope of the graph should be $\rho_l g$. Since the density of water is 1000 kg/m^3, $\rho_l g$ = 9800 N/m^3. However, the pressure readings were taken in kPa, so we expect the slope to be 9.8 kN/m^3 (kN = kilonewtons). Record the experimental value of the slope in the "Data" section, and compare it with the theoretical value.

PROCEDURE PART 2: BUOYANCY

In this part, you will determine whether the buoyant force exerted by water on a submerged block depends on the density of the block.

1. Using the Vernier calipers, measure the dimensions of the aluminum block, and calculate its total volume.

2. Pour water into the beaker until it is almost full. Attach the aluminum block to the spring scale with its longest dimension vertical, and lower the block very slowly into the beaker. Record the reading of the spring scale when the block is 1/5, 2/5, 3/5, 4/5, and fully submerged in water, using the 1-cm marks along the block as a guide, and convert these readings into weight (in SI units of Newtons). Determine the displaced volume of water for each case.

3. Using the known densities of aluminum (2700 kg/m^3) and water (1000 kg/m^3), plot the apparent weight F_s of the block as a function of the displaced volume of water V_d. (Recall that the apparent weight is equal to the reading of the spring scale converted into SI units of newtons.) Make a best-fit line through your data points, and calculate the slope of this line. How well does your graph obey a linear fit? Determine the theoretical slope of the line from Eq. 5, and compare it with your experimental value.

4. Repeat steps 1 – 3 with the brass block (of density 8400 kg/m^3).

5. Based on your results above, comment on whether the buoyant force depends on the density of the block.

PROCEDURE PART 3: IDEAL GAS AND ABSOLUTE ZERO

1. Safety Considerations: When the experimental steps below call for "hot water", use hot tap water or water heated by the electric tea kettles to 70 – 80 °C: hot to the touch, but not scalding hot. Use great care not to spill or splash water on the keyboard or other computer equipment. Clean up any splashed or spilled water immediately with a sponge and/or paper towels.

2. Determining Absolute Zero: You will be producing a graph of pressure as a function of temperature, then extrapolating the graph to zero pressure to determine the value of absolute zero.

   a. Fill the electric tea kettle with water from the faucet in the lab room. Connect the low-pressure sensor to the tube from the cylindrical copper can, fix the thermometer sensor to the can using rubber bands or tape, and submerge the can in the water inside the kettle.

   b. Get a new Capstone page. Set up the "Temperature Sensor" and "Pressure Sensor, Low" in channels A and B of the interface, and have them take data once per second (change the sample rate at the bottom of the screen to 1 Hz). Turn on the tea kettle and start recording data. Record until the pressure changes by about 8 kPa, then stop recording and turn off the kettle. (The data should look linear.) While recording you can perform the next steps below.

   c. During or after recording your data, you can set up the calculation for your graph. You will plot a graph of temperature versus pressure. The pressure sensor measures deviations from the ambient atmospheric pressure in kPa. But since you need the total pressure, you will have to add the ambient atmospheric pressure to your reading. Read the barometer in the room, and convert the reading to kPa. The conversions below may help:

$$1 \text{ bar} = 10^5 \text{ Pa} = 100 \text{ kPa}. \tag{8}$$

$$1 \text{ atm} = 1.013 \times 10^5 \text{ Pa} = 101.3 \text{ kPa} = 0.760 \text{ m of mercury}. \tag{9}$$

   d. Select your data using the "Highlight range of points..." tool. Click on the "Apply selected curve fits..." tool and choose "Linear". A box should appear telling you the slope and y-intercept of the best-fit line.

   e. Add the ambient atmospheric pressure to the y-intercept value of your best-fit line. Use the slope obtained from the best-fit line and this new y-intercept to calculate the estimate of absolute zero, $T_0 = -b/m$. Calculate your experimental error using the known value of absolute zero.

DATA

Procedure Part 1:

3. Pressure at depth of 0.72 m = ______________________________

   Pressure at depth of 0.67 m = ______________________________

   Pressure at depth of 0.62 m = ______________________________

   Pressure at depth of 0.57 m = ______________________________

   Pressure at depth of 0.52 m = ______________________________

   Pressure at depth of 0.47 m = ______________________________

   Pressure at depth of 0.42 m = ______________________________

   Pressure at depth of 0.37 m = ______________________________

   Pressure at depth of 0.32 m = ______________________________

   Pressure at depth of 0.27 m = ______________________________

   Pressure at depth of 0.22 m = ______________________________

   Pressure at depth of 0.17 m = ______________________________

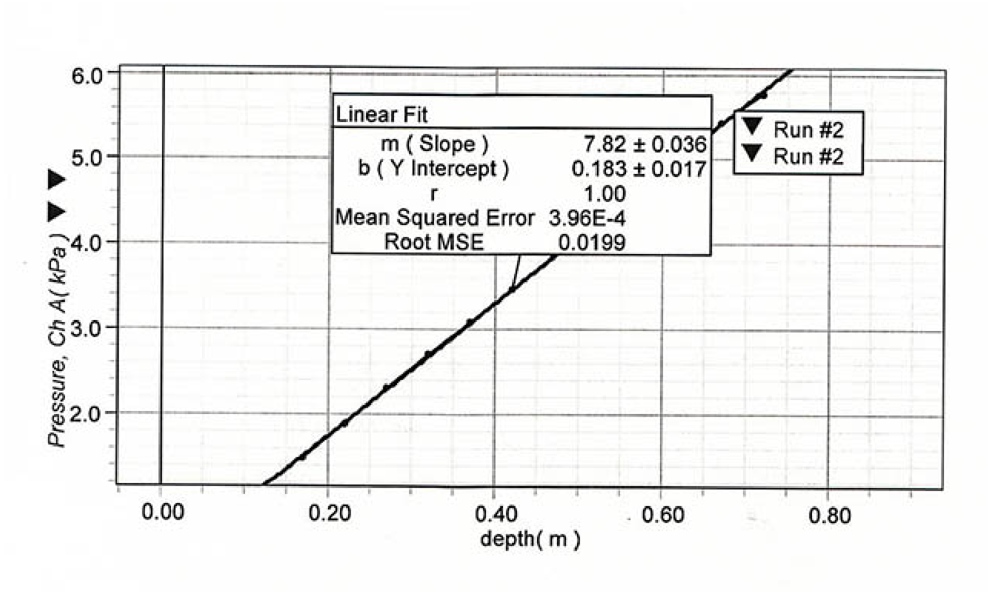
4. Pressure at depth of 0.00 m = ______________________________

5. Slope of line (experimental) = ______________________________

   Slope of line (theoretical) = ______________________________

   Percentage difference in slope of line = ______________________________

   You may print the data table and graph showing pressure as a function of depth.



Procedure Part 2:

1. Dimensions of aluminum block = ______________________________

   Volume of aluminum block = ______________________________

2. Reading of spring scale when aluminum block is 1/5 submerged = ________________________

   Reading of spring scale when aluminum block is 2/5 submerged = ________________________

   Reading of spring scale when aluminum block is 3/5 submerged = ________________________

   Reading of spring scale when aluminum block is 4/5 submerged = ________________________

   Reading of spring scale when aluminum block is fully submerged = _______________________

   Displaced volume of water when aluminum block is 1/5 submerged = _____________________

   Displaced volume of water when aluminum block is 2/5 submerged = _____________________

   Displaced volume of water when aluminum block is 3/5 submerged = _____________________

   Displaced volume of water when aluminum block is 4/5 submerged = _____________________

   Displaced volume of water when aluminum block is fully submerged = ____________________

3. Slope of best-fit line = ______________________________

   Theoretical slope of line = ______________________________

   Percentage difference in slope of line = ______________________________

4. Dimensions of brass block = ______________________________

   Volume of brass block = ______________________________

   Reading of spring scale when brass block is 1/5 submerged = ___________________________

   Reading of spring scale when brass block is 2/5 submerged = ___________________________

   Reading of spring scale when brass block is 3/5 submerged = ___________________________

   Reading of spring scale when brass block is 4/5 submerged = ___________________________

   Reading of spring scale when brass block is fully submerged = __________________________

   Displaced volume of water when brass block is 1/5 submerged = _________________________

   Displaced volume of water when brass block is 2/5 submerged = _________________________

   Displaced volume of water when brass block is 3/5 submerged = _________________________

   Displaced volume of water when brass block is 4/5 submerged = _________________________

   Displaced volume of water when brass block is fully submerged = ________________________

   Plot the graph of F_{s} as a function of V_{d} using one sheet of graph paper at the end of this workbook. Remember to label the axes and title the graph.

   Slope of best-fit line= ______________________________

   Theoretical slope of line = ______________________________

   Percentage difference in slope of line = ______________________________

5. Does the buoyant force depend on the density of the block?

   ____

   ____

   ____

The Photoelectric Effect

APPARATUS

- Photodiode with amplifier
- Batteries to operate amplifier and provide reverse voltage
- Digital voltmeter to read reverse voltage
- Source of monochromatic light beams to irradiate photocathode
- Neutral filter to vary light intensity

INTRODUCTION

The energy quantization of electromagnetic radiation in general, and of light in particular, is expressed in the famous relation

$$E = hf, \tag{1}$$

where E is the energy of the radiation, f is its frequency, and h is Planck's constant (6.63×10^{-34} Js). The notion of light quantization was first introduced by Planck. Its validity is based on solid experimental evidence, most notably the *photoelectric effect*. The basic physical process underlying this effect is the emission of electrons in metals exposed to light. There are four aspects of photoelectron emission which conflict with the classical view that the instantaneous intensity of electromagnetic radiation is given by the Poynting vector $\mathbf{S}$:

$$\mathbf{S} = (\mathbf{E} \times \mathbf{B})/\mu_0, \tag{2}$$

with $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields of the radiation, respectively, and μ_0 ($4\pi\times10^{-7}$ Tm/A) the permeability of free space. Specifically:

1. No photoelectrons are emitted from the metal when the incident light is below a minimum frequency, regardless of its intensity. (The value of the minimum frequency is unique to each metal.)

2. Photoelectrons are emitted from the metal when the incident light is above a threshold frequency. The <u>kinetic energy</u> of the emitted photoelectrons increases with the <u>frequency</u> of the light.

3. The <u>number</u> of emitted photoelectrons increases with the <u>intensity</u> of the incident light. However, the kinetic energy of these electrons is independent of the light intensity.

4. Photoemission is effectively instantaneous.

THEORY

Consider the conduction electrons in a metal to be bound in a well-defined potential. The energy required to release an electron is called the *work function* W_0 of the metal. In the classical model, a photoelectron could be released if the incident light had sufficient intensity. However, Eq. 1 requires that the light exceed a threshold frequency f_t for an electron to be emitted. If $f > f_t$, then a single light quantum (called a *photon*) of energy $E = hf$ is sufficient to liberate an electron, and any residual energy carried by the photon is converted into the kinetic energy of the electron. Thus, from energy conservation, $E = W_0 + K$, or

$$K = (1/2)mv^2 = E - W_0 = hf - W_0. \tag{3}$$

When the incident light intensity is increased, more photons are available for the release of electrons, and the magnitude of the photoelectric current increases. From Eq. 3, we see that the kinetic energy of the electrons is independent of the light intensity and depends only on the frequency.

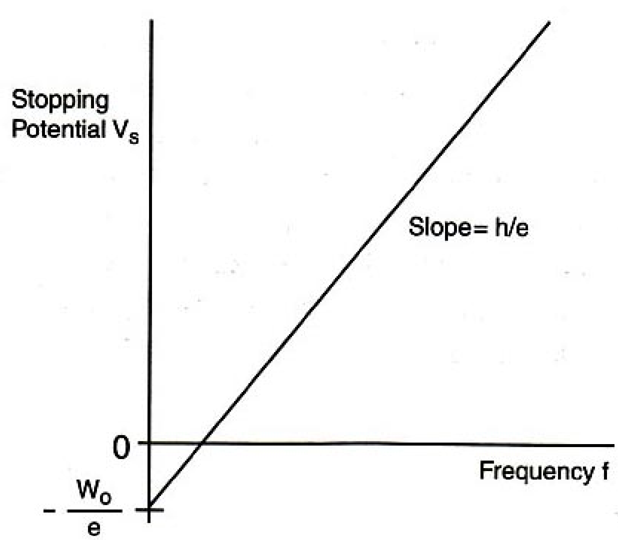
The photoelectric current in a typical setup is extremely small, and making a precise measurement is difficult. Normally the electrons will reach the anode of the photodiode, and their number can be measured from the (minute) anode current. However, we can apply a reverse voltage to the anode; this reverse voltage repels the electrons and prevents them from reaching the anode. The minimum required voltage is called the *stopping potential* V_s, and the "stopping energy" of each electron is therefore eV_s. Thus,

$$eV_s = hf - W_0, \tag{4}$$

or

$$V_s = (h/e)f - W_0/e. \tag{5}$$

Eq. 5 shows a linear relationship between the stopping potential V_s and the light frequency f, with slope h/e and vertical intercept $-W_0/e$. If the value of the electron charge e is known, then this equation provides a good method for determining Planck's constant h. In this experiment, we will measure the stopping potential with modern electronics.



THE PHOTODIODE AND ITS READOUT

The central element of the apparatus is the photodiode tube. The diode has a window which allows light to enter, and the cathode is a clean metal surface. To prevent the collision of electrons with air molecules, the diode tube is evacuated.

The photodiode and its associated electronics have a small "capacitance" and develop a voltage as they become charged by the emitted electrons. When the voltage across this "capacitor" reaches the stopping potential of the cathode, the voltage difference between the cathode and anode (which is equal to the stopping potential) stabilizes.

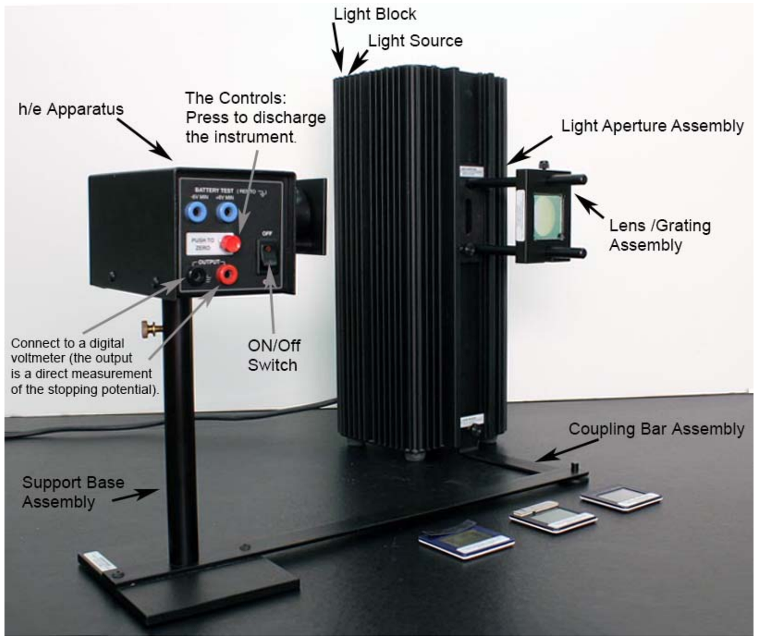
To measure the stopping potential, we use a very sensitive amplifier which has an input impedance larger than 10^{13} ohms. The amplifier enables us to investigate the minuscule number of photoelectrons that are produced.

It would take considerable time to discharge the anode at the completion of a measurement by the usual high-leakage resistance of the circuit components, as the input impedance of the amplifier is very high. To speed up this process, a shorting switch is provided; it is labeled "Push to Zero". The amplifier output will not stay at 0 volts very long after the switch is released. However, the anode output does stabilize once the photoelectrons charge it up.

There are two 9-volt batteries already installed in the photodiode housing. To check the batteries, you can use a voltmeter to measure the voltage between the output ground terminal and each battery test terminal. The battery test points are located on the side panel. You should replace the batteries if the voltage is less than 6 volts.

THE MONOCHROMATIC LIGHT BEAMS

This experiment requires the use of several different monochromatic light beams, which can be obtained from the spectral lines that make up the radiation produced by excited mercury atoms. The light is formed by an electrical discharge in a thin glass tube containing mercury vapor, and harmful ultraviolet components are filtered out by the glass envelope. Mercury light has five narrow spectral lines in the visible region — yellow, green, blue, violet, and ultraviolet — which can be separated spatially by the process of diffraction. For this purpose, we use a high-quality diffraction grating with 6000 lines per centimeter. The desired wavelength is selected with the aid of a collimator, while the intensity can be varied with a set of neutral density filters. A color filter at the entrance of the photodiode is used to minimize room light.



The equipment consists of a mercury vapor light housed in a sturdy metal box, which also holds the transformer for the high voltage. The transformer is fed by a 115-volt power source from an ordinary wall outlet. In order to prevent the possibility of getting an electric shock from the high voltage, do not remove the cover from the unit when it is plugged in.

To facilitate mounting of the filters, the light box is equipped with rails on the front panel. The optical components include a fixed slit (called a light aperture) which is mounted over the output hole in the front cover of the light box. A lens focuses the aperture on the photodiode window. The diffraction grating is mounted on the same frame that holds the lens, which simplifies the setup somewhat. A "blazed" grating, which has a preferred orientation for maximal light transmission and is not fully symmetric, is used. Turn the grating around to verify that you have the optimal orientation.

The variable transmission filter consists of computer-generated patterns of dots and lines that vary the intensity of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

INITIAL SETUP

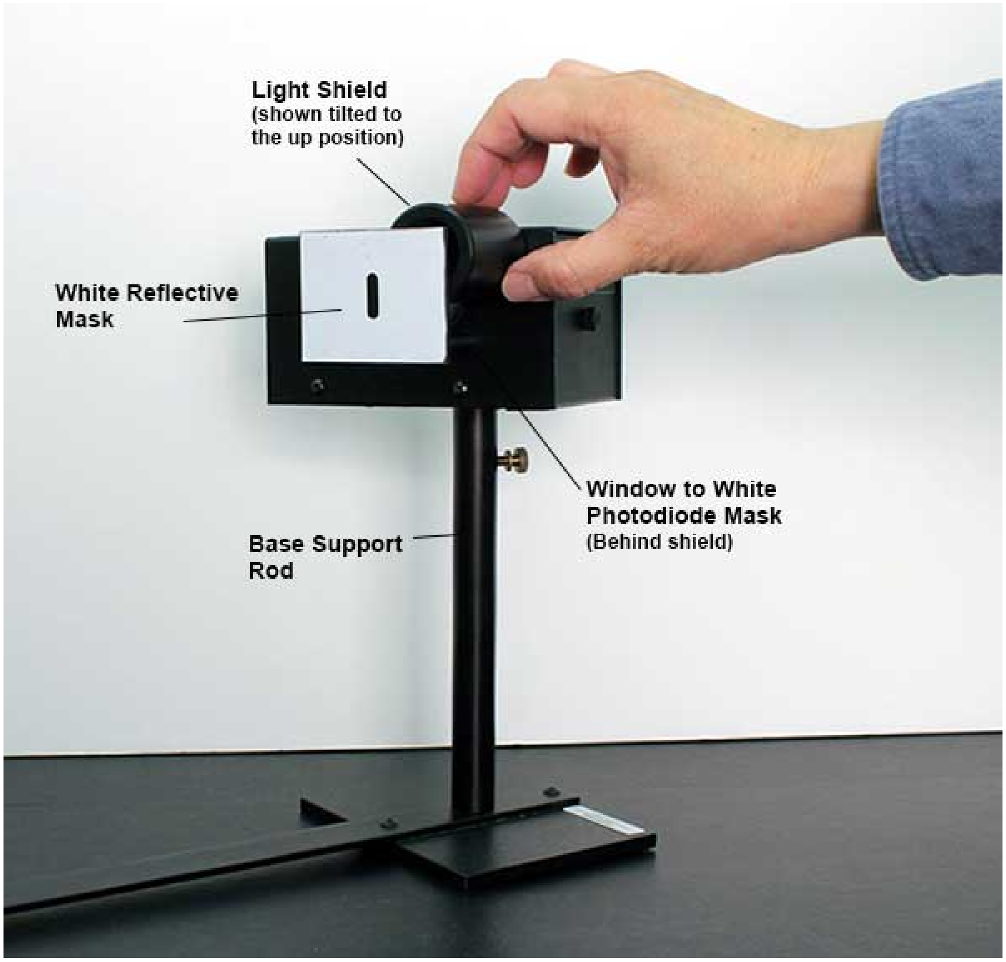
1. Your apparatus should be set up approximately like the figure above. Turn on the mercury lamp using the switch on the back of the light box. Swing the h/e apparatus box around on its arm, and you should see at various positions, yellow green, and several blue spectral lines on its front reflective mask. Notice that on one side of the imaginary "front-on" perpendicular line from the mercury lamp, the spectral lines are brighter than the similar lines from the other side. This is because the grating is "blazed". In you experiments, use the first order spectrum on the side with the brighter lines.

2. Your apparatus should already be approximately aligned from previous experiments, but make the following alignment checks. Ask you TA for assistance if necessary.

   a. Check the alignment of the mercury source and the aperture by looking at the light shining on the back of the grating. If necessary, adjust the back plate of the light-aperture assembly by loosening the two retaining screws and moving the plate to the left or right until the light shines directly on the center of the grating.

   b. With the bright colored lines on the front reflective mask, adjust the lens/grating assembly on the mercury lamp light box until the lines are focused as sharply as possible.

   c. Roll the round light shield (between the white screen and the photodiode housing) out of the way to view the photodiode window inside the housing. The phototube has a small square window for light to enter. When a spectral line is centered on the front mask, it should also be centered on this window. If not, rotate the housing until the image of the aperture is centered on the window, and fasten the housing. Return the round shield back into position to block stray light.



3. Connect the digital voltmeter (DVM) to the "Output" terminals of the photodiode. Select the 2 V or 20 V range on the meter.

4. Press the "Push to Zero" button on the side panel of the photodiode housing to short out any accumulated charge on the electronics. Note that the output will shift in the absence of light on the photodiode.

5. Record the photodiode output voltage on the DVM. This voltage is a direct measure of the stopping potential.

6. Use the green and yellow filters for the green and yellow mercury light. These filters block higher frequencies and eliminate ambient room light. In higher diffraction orders, they also block the ultraviolet light that falls on top of the yellow and green lines.

PROCEDURE PART 1: DEPENDENCE OF THE STOPPING POTENTIAL ON THE INTENSITY OF LIGHT

1. Adjust the angle of the photodiode-housing assembly so that the green line falls on the window of the photodiode.

2. Install the green filter and the round light shield.

3. Install the variable transmission filter on the collimator over the green filter such that the light passes through the section marked 100%. Record the photodiode output voltage reading on the DVM. Also determine the approximate recharge time after the discharge button has been pressed and released.

4. Repeat steps 1 – 3 for the other four transmission percentages, as well as for the ultraviolet light in second order.

5. Plot a graph of the stopping potential as a function of intensity.

PROCEDURE PART 2: DEPENDENCE OF THE STOPPING POTENTIAL ON THE FREQUENCY OF LIGHT

You can see five colors in the mercury light spectrum. The diffraction grating has two usable orders for deflection on one side of the center.

1. Adjust the photodiode-housing assembly so that only one color from the first-order diffraction pattern on one side of the center falls on the collimator.

2. For each color in the first order, record the photodiode output voltage reading on the DVM.

3. For each color in the second order, record the photodiode output voltage reading on the DVM.

4. Plot a graph of the stopping potential as a function of frequency, and determine the slope and the y-intercept of the graph. From this data, calculate W_0 and h. Compare this value of h with that provided in the "Introduction" section of this experiment.

Table of Frequencies and Wavelengths

Color	Frequency (in 10^{14} HZ)	Wavelength (nm)
Yellow	5.187	578
Green	5.490	546
Blue	6.879	436
Violet	7.409	405
Ultraviolet	8.203	365

DATA

Procedure Part 1:

3. Photodiode output voltage reading for 100% transmission = ____________________________

   Approximate recharge time for 100% transmission = ______________________________

4. Photodiode output voltage reading for 80% transmission = ____________________________

   Approximate recharge time for 80% transmission = ______________________________

   Photodiode output voltage reading for 60% transmission = ____________________________

   Approximate recharge time for 60% transmission = ______________________________

   Photodiode output voltage reading for 40% transmission = ____________________________

   Approximate recharge time for 40% transmission = ______________________________

   Photodiode output voltage reading for 20% transmission = ____________________________

   Approximate recharge time for 20% transmission = ______________________________

   Photodiode output voltage reading for ultraviolet light = ____________________________

   Approximate recharge time for ultraviolet light = ______________________________

5. Plot the graph of stopping potential as a function of intensity using one sheet of graph paper at the end of this workbook. Remember to label the axes and title the graph.

Procedure Part 2:

2. First-order diffraction pattern on one side of the center:

Photodiode output voltage reading for yellow light = ______________________________

Photodiode output voltage reading for green light = ______________________________

Photodiode output voltage reading for blue light = ______________________________

Photodiode output voltage reading for violet light = ______________________________

Photodiode output voltage reading for ultraviolet light = ______________________________

3. Second-order diffraction pattern on the other side of the center:

   Photodiode output voltage reading for yellow light = ______________________________

   Photodiode output voltage reading for green light = ______________________________

   Photodiode output voltage reading for blue light = ______________________________

   Photodiode output voltage reading for violet light = ______________________________

   Photodiode output voltage reading for ultraviolet light = ______________________________

4. Plot the graph of stopping potential as a function of frequency using one sheet of graph paper at the end of this workbook. Remember to label the axes and title the graph.

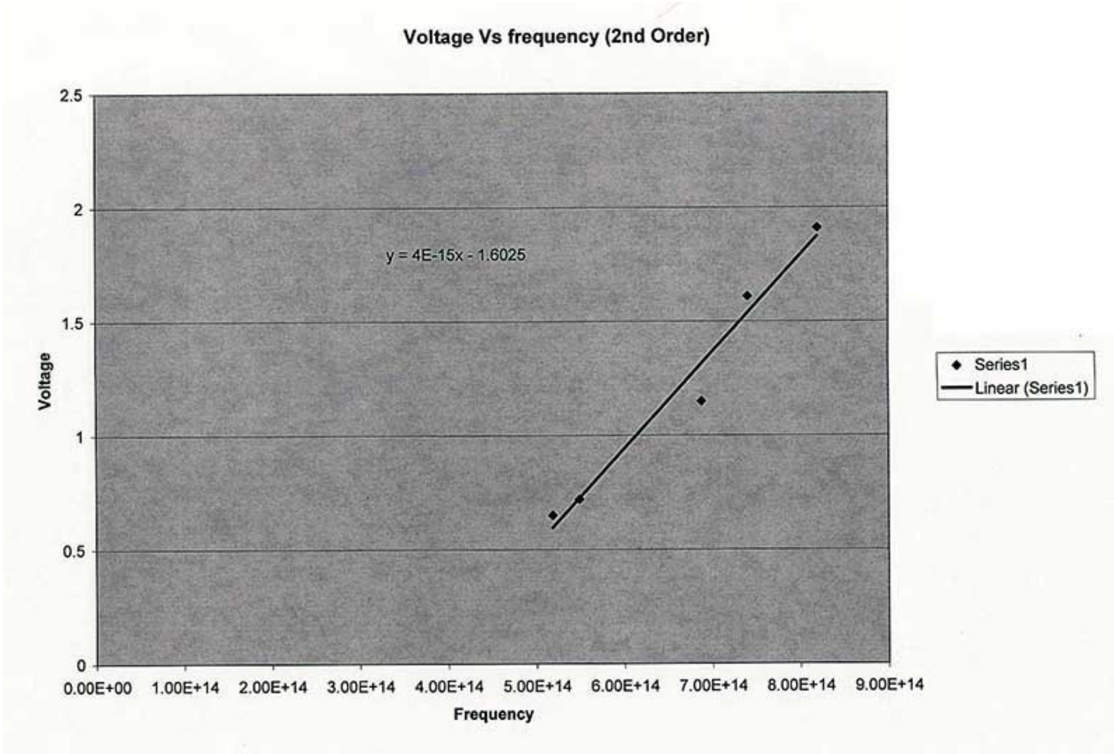
   Slope of graph = ______________________________

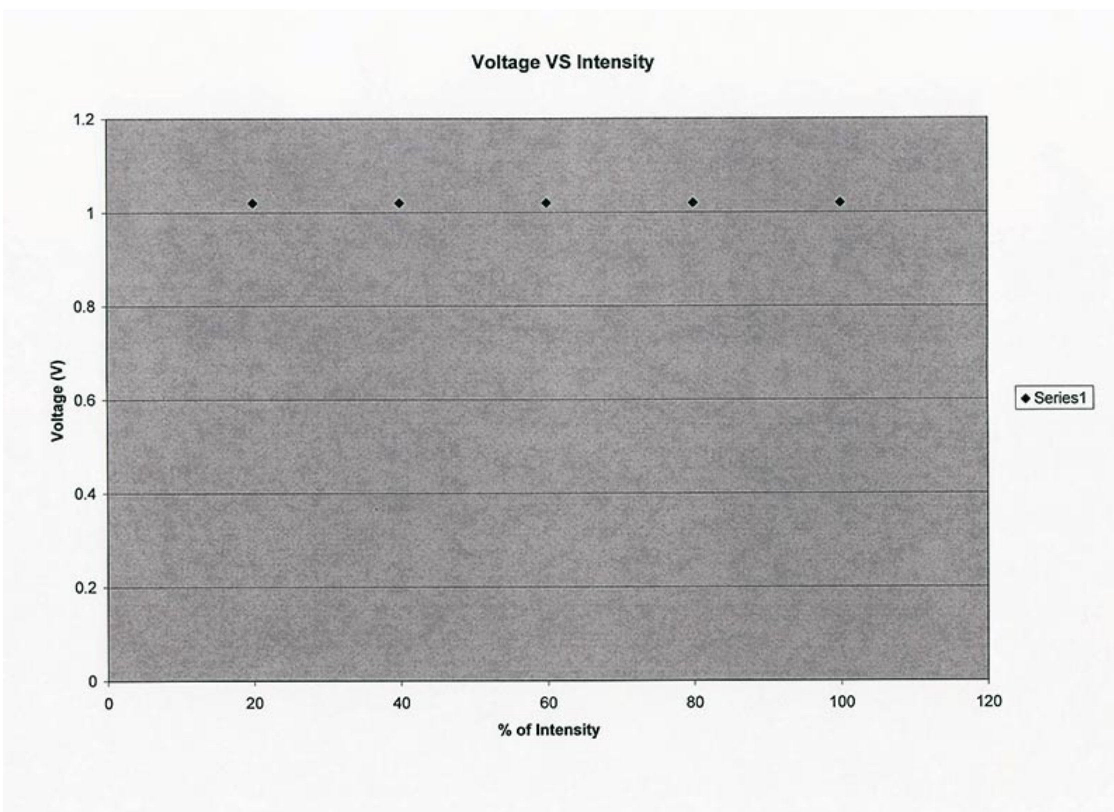
   y-intercept of graph = ______________________________

   W_0 = ______________________________

   h = ______________________________

   Percentage difference between experimental and accepted values of h = __________


Voltage Vs frequency (2nd Order)
y = 4E-15x - 1.6025
Voltage
Frequency
0
0.5
1
1.5
2
2.5
0.00E+00
1.00E+14
2.00E+14
3.00E+14
4.00E+14
5.00E+14
6.00E+14
7.00E+14
8.00E+14
9.00E+14
Series1
Linear (Series1)


Voltage VS Intensity
Voltage (V)
% of Intensity
0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80
100
120
Series1

Radioactivity

APPARATUS

- Computer and interface
- Geiger-Muller detector
- Co and Sr sources
- Source and detector holder
- One in lab: neutron source with bars and silver foil

INTRODUCTION

In this experiment, you will use weak radioactive sources with a radiation counting tube interfaced with the computer to study radioactive decay as a function of time.

RADIATION SAFETY

California State Law requires that a permanent exposure record be filed for all persons who handle radioactive material. Therefore, everyone enrolled in the lab must be registered by the course instructor with the University Environmental Health and Safety Office. Your TA will pass out the radioactive sources for this experiment only after you print your name on the Physics Laboratory Class Roster. You are responsible for the safe return of the sources at the end of the laboratory period. Failure to comply with safety rules or failure to return the sources will result in expulsion from the course and a grade of F.

It is a University of California rule that pregnant women are not permitted to participate in the radioactivity experiment or to be in the lab room where these experiments are performed. If you think you may be pregnant, discuss it privately with your TA. He or she is authorized to excuse you completely from this experiment.

Radioactive materials are potentially dangerous to your health and should always be handled with great caution. It is a prudent practice to wash your hands thoroughly after this experiment is finished.

THEORY

Radioactivity was discovered by Henry Becquerel in 1896. Becquerel found that compounds of uranium would expose a photographic film, even in total darkness. Marie Curie took up the research topic, coined the term radioactivity, and determined that this effect was independent of the chemical compound in which the radioactive element was found and independent of any pressures or temperatures that could be produced. In other words, radioactivity was somehow an internal property of the element itself. Marie Curie later isolated the previously unknown elements polonium and radium, and won two Nobel prizes for her work, the first of which was shared with Becquerel and her husband Pierre Curie. She and other researchers soon established that the energies per atom emitted by radioactive decay were millions of times larger than chemical energies, and that transmutation of the elements was involved.

Early researchers discovered that radiation from natural radioactive elements came in three types: (1) alpha (α) rays, which traveled in a curved path similar to positively charged particles in a magnetic field; (2) beta (β) rays, which traveled in a curved path similar to negatively charged particles in a magnetic field; and (3) gamma (γ) rays, which traveled in a straight line in a magnetic field and were therefore neutral. Today we know that alpha "rays" are helium nuclei, beta "rays" are high-energy electrons, and gamma "rays" are high-energy photons (particles of light). Certain isotopes of radioactive elements emit positive electrons called positrons or β+ particles.

As an example, α particles are emitted in the decay of natural uranium:

$$ {}_{92}\mathrm{U}^{238} \ \rightarrow \ {}_{90}\mathrm{Th}^{234} + {}_{2}\mathrm{He}^{4}. \tag{1}$$

(The ${}_{2}\mathrm{He}^{4}$ nucleus is the α particle.) With the emission of β particles, a neutron changes into a proton (or vice versa) :

$$ {}_{6}\mathrm{C}^{14} \ \rightarrow \ {}_{7}\mathrm{N}^{14} + \mathrm{e}^{-} + \ ? \tag{2}$$

(The e- is the β particle. We will discuss the ? below.) Gamma rays are emitted when an excited state of a nucleus makes a transition to a lower level, in the same way that an atom emits a photon of ordinary light when it is deexcited. Excited states of nuclei are denoted by an asterisk ($*$):

$$ {}_{28}\mathrm{Ni}^{*60} \ \rightarrow \ {}_{28}\mathrm{Ni}^{60} + 2\gamma. \tag{3}$$

The unique characteristics of α, β, and γ particles are responsible for differences in the ways that these particles lose energy when passing through matter. For example, shown below are the typical ranges of 8 million electron-volt (8 MeV) particles in aluminum:

$$ \text{Range in meters: } \alpha = 0.00006\beta = 0.02\gamma = 0.2. \tag{4}$$

The description of β decay given above is actually somewhat incomplete and must be expanded in the context of the range of β particles in matter. While α and γ particles are found to have definite energies (dependent only on the emitter), β particles emitted by a single nuclide can have any energy between zero and some definite maximum value. Careful examination of this fact in the context of a definite decay scheme, such as Eq. 2, led scientists to conclude that β decay violates the three basic conservation laws of energy, momentum, and angular momentum. Enrico Fermi noted in 1934 that if an additional neutral particle were emitted in β decay, the three conservation laws would remain intact. Such neutral particles have actually been found and are called *neutrinos*. Thus, the correct description for the decay in Eq. 2 is

$$ {}_{6}\mathrm{C}^{14} \ \rightarrow \ {}_{7}\mathrm{N}^{14} + \mathrm{e}^{-} + \nu, \tag{5}$$

where ν is the neutrino emitted in β decay.

HALF LIFE

Radioactive substances are unstable. They transmute from one isotope to another by the process of radioactive decay until they reach a stable isotope. The number of nuclei Δn that decay in the subsequent time interval Δt is proportional to the number of non-decayed nuclei $n(t)$ present and to the time interval Δt. Thus, we can write

$$\Delta n = -n(t)\,\lambda\,\Delta t. \tag{6}$$

The minus sign accounts for the fact that $n(t)$ decreases with time, and λ is a proportionality factor called the *decay constant*. Eq. 6 leads to

$$\mathrm{d}n/\mathrm{d}t = -n(t)\,\lambda, \tag{7}$$

which can be integrated to

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where n_0 is the number of nuclei at $t = 0$.

We define the *half-life* $t_{1/2}$ as the time required for half of the parent nuclei to decay. Then

$$n/n_0 = 1/2 = e^{-\lambda t_{1/2}}. \tag{9}$$

Taking the natural logarithm of Eq. 9 leads to

$$\ln(1/2) = -\lambda t_{1/2}, \tag{10}$$

or

$$t_{1/2} = (\ln 2)/\lambda. \tag{11}$$

Since it is easy to obtain λ from the slope of the exponential, Eq. 11 can be used to determine half-lives.

In this experiment, we will be measuring the half-lives of two silver isotopes. The radioactive silver is prepared in the lab by irradiating silver foil with neutrons. A strong neutron source is contained in a heavy shielded tank operated by the radiation safety officer. Inside the tank is a mixture of plutonium and beryllium. The radioactive plutonium emits α particles which react with beryllium according to the scheme

$${}_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 \;\rightarrow\; {}_6\mathrm{C}^{12} + \mathrm{n}. \tag{12}$$

Natural silver consists of the two isotopes ${}_{47}\mathrm{Ag}^{107}$ and ${}_{47}\mathrm{Ag}^{109}$. The neutrons react with them according to these schemes:

$${}_{47}\mathrm{Ag}^{107} + \mathrm{n} \;\rightarrow\; {}_{47}\mathrm{Ag}^{108} \tag{13}$$

$${}_{47}\mathrm{Ag}^{109} + \mathrm{n} \;\rightarrow\; {}_{47}\mathrm{Ag}^{110}. \tag{14}$$

Some of the silver is produced in an excited state, and both isotopes decay via β and γ emission, but with very different half-lives. The decay schemes for the isotopes are as follows:

$$
\begin{aligned}
{}_{47}\mathrm{Ag}^{108} &\rightarrow {}_{48}\mathrm{Cd}^{108} + \mathrm{e}^{-} + \nu && \text{short half-life (seconds)} && (15)\\
{}_{47}\mathrm{Ag}^{*108} &\rightarrow {}_{48}\mathrm{Cd}^{108} + \mathrm{e}^{+} + \nu && \text{greater than 5-year half-life} && (16)\\
{}_{47}\mathrm{Ag}^{110} &\rightarrow {}_{48}\mathrm{Cd}^{110} + \mathrm{e}^{-} + \nu && \text{short half-life (seconds)} && (17)\\
{}_{47}\mathrm{Ag}^{*110} &\rightarrow {}_{48}\mathrm{Cd}^{110} + \mathrm{e}^{-} + \nu && \text{253-day half-life.} && (18)
\end{aligned}
$$

In each case where an isotope of cadmium (Cd) is produced by β decay, the nucleus is formed highly excited. The nuclei are stabilized by subsequent γ emission, where the half-life is very much shorter than a microsecond. Hence, the decay rates of the radioactive silver isotopes to the stable isotopes of cadmium are completely governed by β decay.

As you can see from the decay schemes above, there are actually <u>two</u> different ways each isotope of silver can undergo β decay. One method, corresponding to the long half-life, is relatively improbable. The other method, however, occurs quite often and implies a relatively short half-life (of the order of minutes). In this part of the experiment, you will determine the short half-lives of the radioactive silver isotopes.

The proportion of two short-lived cadmium isotopes present in your specimens after irradiation depends on the probability of process 13 compared with process 14, and also on the relative concentrations of the two silver isotopes in the sample. Rather than determining the concentration of each isotope separately and studying its decay, we will utilize a simple and useful technique for half-life determinations that depends only on an accurate measurement of the variation of count rate with time.

In half-life measurements (which we will perform below), Eq. 8 gives the number of parent radioactive material left after a time t:

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where λ is related to the half-life. A common goal is to determine the slope λ of the exponential. Exponential relationships such as these are common in scientific work, so we would like a rapid way of obtaining the slope and checking the fit. If we plot them on ordinary graph paper, then the slope would be the curve of the exponential. A curve-fitting program could fit an exponential to the experimental curve and determine the value of the slope, but it would still be difficult to see at a glance how good the fit is.

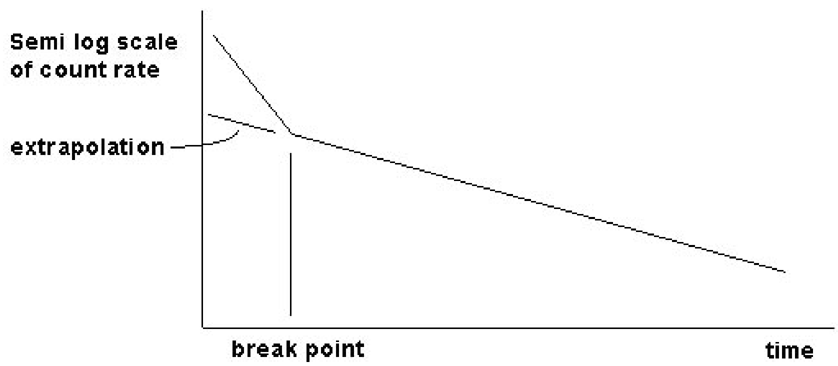
Instead, we will plot these relationships on a special kind of graph: a *semilog* graph. In a semilog graph, the exponential relationship becomes a straight line. The y-axis is the logarithm of the dependent variable, and the x-axis is the independent variable treated in the normal linear manner. Taking the natural logarithm of Eq. 8, we find

$$\ln n(t) = \ln n_0 - \lambda t. \tag{19}$$

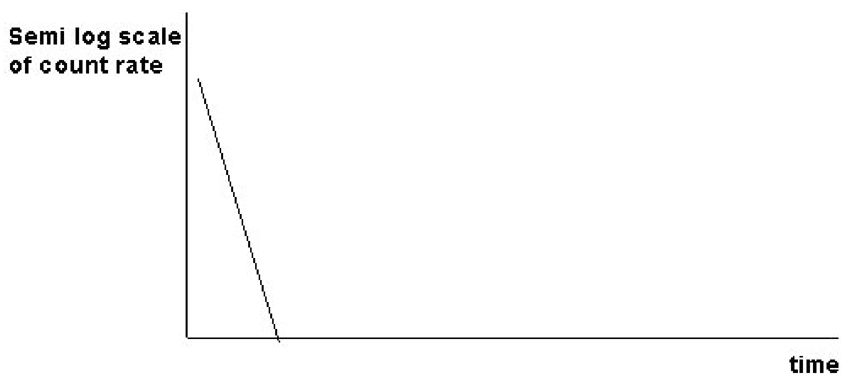
Note that the logarithm of the dependent variable ($n(t)$ in this case) now satisfies a linear relation, and can therefore be plotted as a straight line on a semilog graph. In addition, the slope of the semilog graph is equal to the coefficient $-\lambda$ of the exponential.

If the radioactive decay of only a single isotope were involved, then a semilog plot of the count data as a function of time would look as follows:

The slope of the exponential is the negative of the decay constant λ, and the half-life can be determined from Eq. 11. In our case, two isotopes are decaying at different rates, so the semilog plot looks more like Figure 2:



At long times, the slope of the graph is controlled by the longer of the two half-lives. This is sufficient to determine the long half-life, since essentially all of the short-lived isotope has decayed. By extrapolating this longer time region back to $t = 0$, one can subtract out the effect of the long-lived isotope. This corresponds to determining the contribution of the long-lived isotope to the full rate at each time and subtracting it out. From a semilog plot of the remaining data, one can determine the short half-life from the slope of its exponential:



ANALYSIS WITH SEMILOG PLOTS

Some of the older Excel programs will perform semilog plots directly, but other recent versions do not have this feature. It is possible to do a semilog plot by hand on special semilog graph paper. However, once we have a list of the count data in an Excel column, we can simply take the logarithms of the data in the next column with the "Fill Down" operation and plot the logarithms of the counts as functions of time.

By convention, base 10 logarithms are written as just "log" (no subscript), and logarithms of base

$e = 2.718\ldots$ are written as "ln". Our purpose in plotting the semilog graph of the count data is to determine the break point, as in Figure 2. Therefore, it does not matter whether we take the base 10 logarithms (log) or the base e logarithms (ln), since these quantities are related by a constant. Either the log or ln of the count data as functions of time will plot as a straight line (for a single isotope).

The basic definition of the logarithm function gives

$$x = b^{\log_b x}, \tag{20}$$

where $\log_b$ is base b logarithm. Using $x = e \ln x$, we find a conversion between base 10 logarithms (log) and natural logarithms (ln) :

$$\log x = (\log e)(\ln x). \tag{21}$$

Since the different base logarithms are related by a constant ($\log e$), data that plot as a straight line in one base will also plot as a straight line in the other base.

STATISTICS IN RADIOACTIVITY MEASUREMENTS

The process of radioactive decay is completely random. Quantum mechanics can predict the probability of a decay per second, but the time at which any particular nucleus decays cannot be predicted, even in principle. Thus, with a sample of radioactive material, the number of nuclei that will probably decay in any time period (such as the 10-second intervals we will be using in the experiments below) is determined by the half-life, but there will be random variations in the number that decay in any particular 10-second interval. The same is true of the background radiation from cosmic rays and terrestrial radioactivity: the counts detected by a Geiger counter come at random, although they have a *mean* or average rate. For example, here is a list of the counts during 10-second intervals, taken in the Knudsen nuclear lab, where the neutron source and several other sources are stored:

$$9, 18, 7, 13, 8, 11, 8, 8, 9, 12, 5, 8, 5, 13, 9, 8, 9, 12, 9, 6, 8, 5, 8, 15, 10, 5, 11, 12, 9, 8.$$

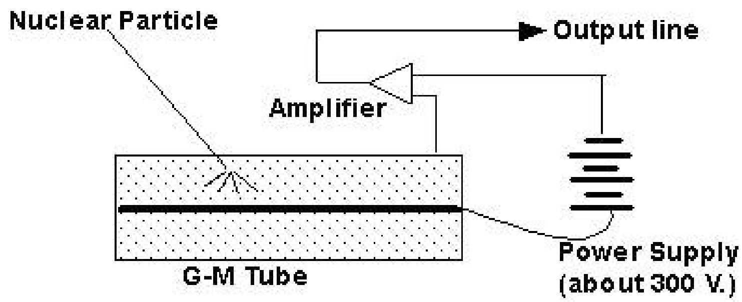
The computer calculates quickly and automatically the mean number of counts as 9.3, but also gives another number called the *standard deviation* (denoted by σ). The standard deviation is a measure of the spread in the number of counts. For the numbers above, $\sigma = 3.1$. This means that 68% of the counts in any 10-second interval fall between (9.3 – 3.1) counts and (9.3 + 3.1) counts. Please refer to the additional credit section for more discussion.

The standard deviation has an exact definition in the science of statistics. In fact, when any experimental measurement is taken, there will be a spread in the values of the measurements along a bell-shaped curve that can be described by a standard deviation. An example is if we had a large number of students measure the length of the same lab bench with a meter stick; we would find that these measurements also fit a bell-shaped curve with a mean and standard deviation.

THE GEIGER-MULLER TUBE

The experiments below use a Labnet Geiger-Muller (GM) detector which is plugged into one of the digital channels of the Pasco signal interface. When you look into the transparent cylinder of the detector, the actual GM tube is the copper cylinder at the bottom end, which appears similar to a large bullet cartridge. The rest of the electronics inside the transparent tube consists of the power supply for the GM tube which operates at 300 – 400 V DC, and the digital interface that amplifies the GM pulses and converts them to digital pulses accepted by the signal interface box.

The GM tube is a closed cylinder containing a gas mixture which includes a halogen compound. A thin wire filament is aligned along the tube axis and maintained at a large positive voltage with respect to the outer wall. When an ionizing particle (α, β, or γ) passes through the gas, ion-electron pairs are created. The electrons are quickly drawn to the center wire by the strong electric field, where they are collected as a "pulse" of current.



This current pulse is electronically amplified and then sent on to the signal interface. Another function of the gas is to quench the electrical breakdown quickly so that the system can count successive pulses separated in time by very small intervals. Halogens are found to be particularly effective for this purpose.

Because β rays are easily stopped by the outer metal cylindrical shell, it is necessary to construct the GM tube with a very thin (about 1.5 mg/cm2) mica window at one end. <u>Be careful with this end window, as it is easily damaged, rendering the tube useless and irreparable.</u>

PROCEDURE PART 1: THE NUCLEAR SENSOR

Pasco's generic name for the GM detector is "Nuclear Sensor". The device itself is labeled "GM - Detector". However, in the analog sensor menu of the Capstone, it is called a "Geiger Counter". These names all refer to the same instrument.

The device has a plastic cap over the detector end for protection. The actual GM tube is recessed in the plastic cylinder at the end of the detector. Remove the plastic cover for use, and replace it when you are finished. <u>The GM tube itself has a delicate, thin mica window at its end through which radiation passes. If this window is damaged, the tube is ruined, so be careful not to poke anything into the plastic cylinder or to push the tube toward anything that pokes out.</u>

1. Turn on the interface and the computer.

2. Call up Capstone.

3. The GM detector has a line-cord plug and a phone-cord interface to the digital plug which

goes into the signal interface. When the line cord of the GM detector is plugged in, a neon bulb inside lights up, indicating that the instrument has power. The other neon bulb flashes intermittently as each count is detected. This happens whether or not you are recording or monitoring and even if there are no radioactive materials nearby, because the tube detects stray cosmic rays and terrestrial radioactivity that are always present.

4. Choose the "Table & Graph" option in Capstone. Under "Hardware Setup", click on Channel 1 of the interface and select "Geiger Counter". At the bottom of the screen, change the sample time to 10 seconds. This will give you one measurement every 10 seconds of recording time. Click on the y-axis of the graph and select "Geiger Counts (counts/sample)". Click on "Select Measurement" in your table and choose "Geiger Counts (counts/sample)". If your watch has a continuously illuminated night dial, it may contain a small amount of radioactive material. Check the watch with the detector if you wish, and take it off and move it some distance away if you find that it is radioactive.

5. Move all radioactive materials at least one meter from the detector and take a background count by clicking "Record" and counting for 100 – 120 seconds. Then click "Stop". Your table should now have approximately 10 entries for the count every 10 seconds.

6. When you click the $\sum$ symbol on the table, the computer will calculate the mean count and standard deviation below (along with the minimum and maximum count). Record the mean background count and its standard deviation. Your count will be higher than "normal" if your lab station is close to the neutron source used in the half-life measurement below.

   Background count (mean) = ______________________________

   Standard deviation = ______________________________

PROCEDURE PART 2: HALF-LIFE MEASUREMENTS

(The instructions for Excel are abbreviated, as it is assumed that you are familiar with the operations.)

1. Check that you are counting for 10-second intervals. Prepare your computer to start taking count data on the next mouse click by setting the mouse arrow on the "Record" button.

2. When you are ready, the radiation safety officer will hand you a rod with the activated silver foil on the end. As quickly as possible, but still being careful, place the rod in the holder with the silver close to the GM counter, and click to start recording. Stop after approximately 10 minutes.

3. Copy the silver count data from your table into a column of a new Excel worksheet.

4. Subtract out the background count in the next column of the worksheet.

5. Use the "Fill Series" operation to fill the next column of the worksheet with the time of the center of the 10-second intervals (i.e., 5, 15, 25, etc.), up to 10 minutes.

6. Use the "Fill Down" operation to take the logs or lns of the count data (it doesn't matter which) in the next column.

7. Chart the logs of the data as functions of time. (Select and chart the last two columns.) This semilog chart should look something like Figure 2: a straight line of steeper slope breaking to a line of shallower slope, corresponding to the two half-lives involved. The data at large times is likely to look ragged due to fluctuations in the statistics. We now wish to extract the two half-lives.

8. Locate the break point in time where the slope changes at about 150 seconds.

   Break point = ______________________________

9. Back in Excel, select and chart only count data after the break point. (Chart the actual data, not their logs.) Select the data points on the chart, and use the trendline operation to fit an exponential curve. Check the box for "Equation on Chart" to obtain the slope of the exponential. From this slope, extract the longer half-life using Eq. 11, and record this half-life below.

   Longer half-life = ______________________________

10. To obtain the shorter half-life, start a new column in Excel, and subtract from the background-corrected data, the data for the longer half-life using the equation that you obtained in step 10. (Your entry before "Fill Down" will look something like "= C4 - 609*exp(-0.0035*B4)".)

11. Chart the resulting data, and extract the shorter half-life as before with the trendline operation.

    Shorter half-life = ______________________________

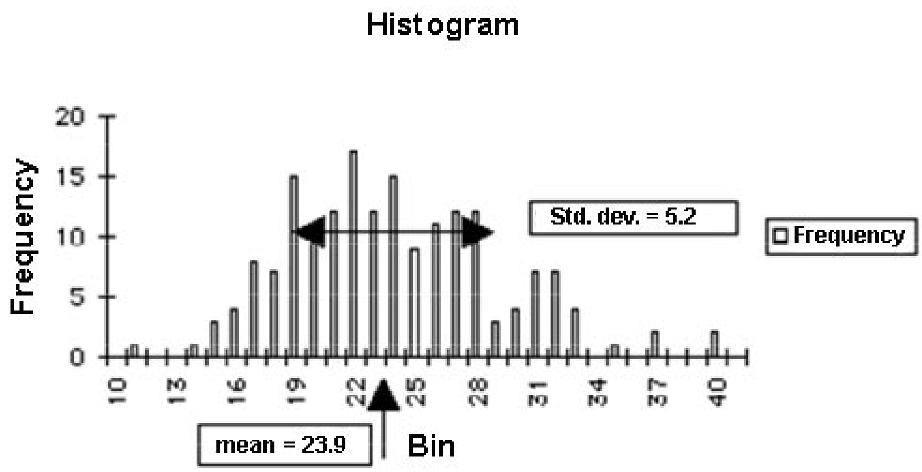
12. Rearrange your Excel tables and charts neatly on one or two sheets.

ADDITIONAL CREDIT: HISTOGRAM OF NUCLEAR STATISTICS (up to 3 mills)

Prepare an annotated histogram of radiation counting data in Capstone (2 mills) or Excel (3 mills). The additional credit is for figuring out how to do this without the help of your TA.

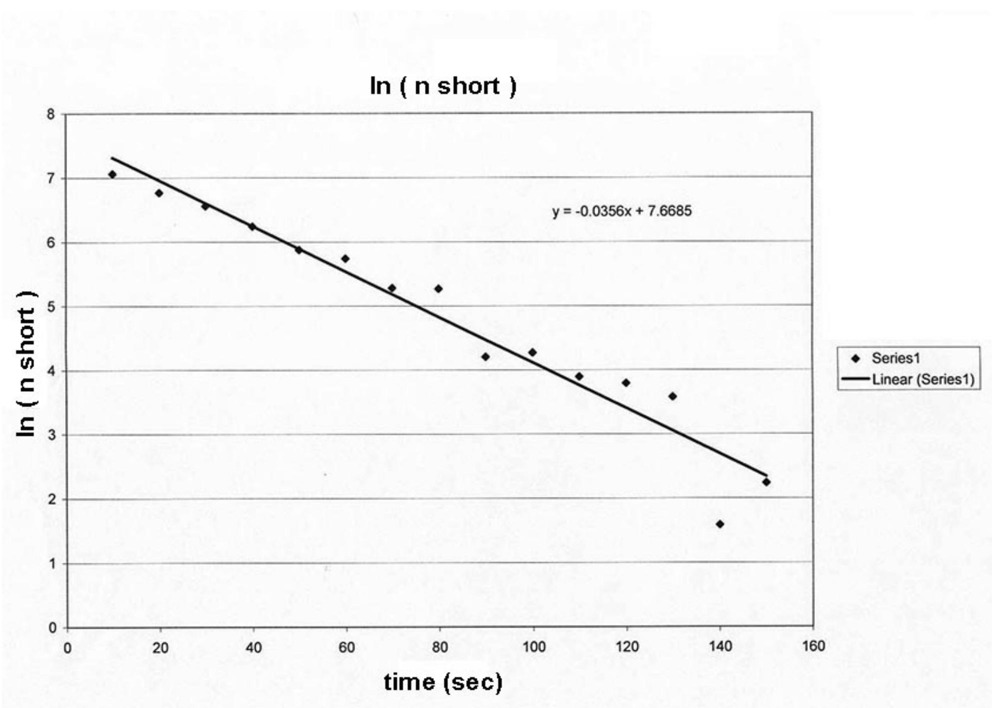
Obtain a sample of radioactive material in plachet form from the radiation officer, and place it near the GM counter front. Arrange the GM tube, plachet, and shielding pieces so that you are obtaining a fair number of counts in the 10-second intervals (say, 50 – 100). Count for 10 minutes or so.

Calculate the mean count and standard deviation. Use the "Help" sections of the programs if needed. For Excel, pull the "Tools" menu down to "Data Analysis", and choose "Histogram". Follow the instructions, using the "Help" function as necessary. Below is a sample histogram.



Annotate your graph with the mean and standard deviation. For Excel, you need to use the "Draw" and "Text Box" functions to put in the mean and standard deviation in some nice way, perhaps even better than shown above. (Note that this histogram, which is based on 30 minutes of counting, will probably be "smoother" than one based on 10 minutes of counting.)

RETURN YOUR RADIOACTIVE PLACHET TO THE RADIATION OFFICER.



Time (s)	counts (delta n total)	counts - bg (n = n total - n bg)	ln (n)	n long	n short	ln (n short)
10	1588	1582	7.366445	414.304	1167.696	7.062788
20	1271	1265	7.142827	394.4924	870.5076	6.769076
30	1088	1082	6.986566	375.6283	706.3717	6.560142
40	878	872	6.770789	357.6661	514.3339	6.242873
50	703	697	6.546785	340.563	356.437	5.876158
60	642	636	6.455199	324.2776	311.7224	5.742113
70	511	505	6.224558	308.771	196.229	5.279282
80	494	488	6.190315	294.0059	193.9941	5.267827
90	353	347	5.849325	279.9469	67.05308	4.205485
100	344	338	5.823046	266.5602	71.43983	4.268856
110	309	303	5.713733	253.8136	49.18644	3.895618
120	292	286	5.655992	241.6765	44.32351	3.791515
130	272	266	5.583496	230.1198	35.88021	3.580186
140	230	224	5.411646	219.1157	4.884278	1.586022
150	224	218	5.384495	208.6379	9.362145	2.236674
160	186	180	5.192957	198.661	-18.66103	
170	204	198	5.288267	189.1613	8.838717	
180	212	206	5.327876	180.1158	25.8842	
190	144	138	4.927254	171.5029	-33.50287	
200	158	152	5.023881	163.3018	-11.3018	
210	152	146	4.983607	155.4929	-9.492889	
220	127	121	4.795791	148.0574	-27.05739	
230	148	142	4.955827	140.9775	1.022543	
240	150	144	4.969813	134.2361	9.763925	
250	146	140	4.941642	127.8171	12.18294	
260	155	149	5.003946	121.705	27.29501	
270	132	126	4.836282	115.8852	10.11481	
280	102	96	4.564348	110.3437	-14.3437	
290	115	109	4.691348	105.0672	3.932815	
300	92	86	4.454347	100.043	-14.04299	
310	124	118	4.770685	95.25905	22.74095	
320	128	122	4.804021	90.70387	31.29613	
330	110	104	4.644391	86.36651	17.63349	
340	76	70	4.248495	82.23656	-12.23656	
350	80	74	4.304065	78.3041	-4.304103	
360	84	78	4.356709	74.55969	3.440311	

370	92	86	4.454347	70.99433	15.00567
380	86	80	4.382027	67.59946	12.40054
390	70	64	4.158883	64.36693	-0.366931
400	64	58	4.060443	61.28898	-3.288977
410	54	48	3.871201	58.35821	-10.35821
420	71	65	4.174387	55.56758	9.432417
430	56	50	3.912023	52.9104	-2.910404
440	46	40	3.688879	50.38029	-10.38029
450	36	30	3.401197	47.97116	-17.97116
460	54	48	3.871201	45.67723	2.322767
470	60	54	3.988984	43.493	10.507
480	54	48	3.871201	41.41321	6.586786
490	48	42	3.73767	39.43288	2.567119
500	48	42	3.73767	37.54724	4.452755
510	40	34	3.526361	35.75178	-1.751778
520	46	40	3.688879	34.04217	5.957832
530	38	32	3.465736	32.41431	-0.41431
540	40	34	3.526361	30.86429	3.135705
550	36	30	3.401197	29.3884	0.611601
560	38	32	3.465736	27.98308	4.016921
570	24	18	2.890372	26.64496	-8.64496
580	28	22	3.091042	25.37083	-3.370828
590	36	30	3.401197	24.15762	5.842377
600	30	24	3.178054	23.00243	0.997567