Physics 120 Heat, Waves, and Light

# Laboratory Manual

Winter 2025

Knox College Department of Physics & Astronomy

ii

## Physics 120 - Heat, Waves, & Light Laboratory Manual

Winter 2025

DEPARTMENT OF PHYSICS & ASTRONOMY KNOX COLLEGE Galesburg, Illinois

ii

### Contents

1. Preface	$\mathbf{v}$
2. Laboratory Course Information	vii
3. Preparing Laboratory Reports	ix
4. Significant Digits	xiii
5. Error Analysis	xv
6. Linear Interpolation	xix
7. Experiment 1 - Thermal Expansion of Metals	1
8. Experiment 2 - Ideal Gases: Laws of Boyle and Gay-Lussac	7
9. Experiment 3 - Specific Heat of Metals	11
10.Experiment 4 - Latent Heat of Fusion and Vaporization	15
11.Experiment 5 - Simple Harmonic Oscillations of a Mass-Spring System	19
12.Experiment 6 - Standing Waves on a String	25
13.Experiment 7 - Geometric Optics	29
14.Experiment 8 - Interference and Diffraction of Light	35

iv

### PREFACE

The goals of physics are to understand nature and partly such that we can make accurate predictions about nature. Physicists often set about pursuing these goals by reasoning mathematically from a small set of fundamental laws which look much like mathematical axioms. Because of this emphasis on mathematical reasoning and logical deduction, it is easy to lose sight of the crucial fact that physics, like the other sciences, is **experimental**. This means that experiments are the basis for the laws of physics and all the predictions we derive from them – the "laws" are in essence just concise summaries of experimental results – and in this way, they are quite different from mathematical axioms. When a theoretical prediction conflicts with an experimental finding, it is always the theory which must be discarded – so *experiments constrain theory*. It is experiment which sorts out which theories are possible and which are not. Naturally, the real story is often more complicated than this simple picture: there are examples of great theorists who refused to believe in experiments that seemed to contradict their views and whose intuitions about nature were ultimately vindicated by more careful later experiments. There have also been some great theorists who tried this dangerous game and lost. Notwithstanding these interesting complexities of physics research as a human endeavor plagued with fascinating individual cases that challenge any generality we state, the fundamental principle remains that experiments are the ultimate basis of our physical knowledge.

Real experiments are also a messy business. It is almost never easy to disentangle a single phenomenon or principle to be tested from all the other interactions and phenomena that are always present. Right away we are forced to make approximations, to try to neglect interactions that are hopefully small (like air resistance), and to model others that may not be small (like sliding friction) in ways that we know are imperfect. There is always the issue of choosing an appropriate model (i.e. a mathematical description of the experiment that inevitably leaves some things out). Of course, one wants to be sure that what is left out is in fact negligible, or, more precisely, one wants to have some estimate of the size of the errors made. So good experiment design involves error analysis, which can be surprisingly intricate. In this course you will encounter some of these issues of experiment design and uncertainty analysis, but our focus will be primarily on the using the physics you learn in the classroom to understand real phenomena in the lab. Applying the tools and techniques you learn in the classroom to analyzing your experiments will give you good practice in using the physics you are learning.

This manual begins with information about the course policies and instructions for preparing your lab reports. This is a good place to check if you have questions about what is expected in your reports. The introductory section also includes some general information about reporting measured numbers properly and analyzing experimental uncertainties. Make sure to also look over this information while preparing your reports. Descriptions of the weekly laboratory experiments follow.

vi

### LABORATORY COURSE INFORMATION

Knox College Physics 120 - Winter 2025

LAB MEETINGS: Wednesdays in room SMC D105

LAB INSTRUCTOR: Tom Moses, SMC D116, x7341, email: tmoses@knox.edu

LAB REPORT HONOR CODE POLICY: You are encouraged to work together on lab reports; you may consult other students as well as tutors, other physics faculty, etc in addition to your textbook as well as other reference material such as textbooks in the library or in the physics lounge. However, you may only exchange data with a lab partner that was present when you collected the data. Your final write-up must be your own unique product. In particular, duplicate reports, even from lab partners, are not acceptable. Likewise, sharing any exact text or plots from your report is not acceptable. And the use of AI in preparing lab reports is strictly prohibited.

**LAB REPORT SUBMISSION:** Lab Reports are due on the following Friday at 4:00PM. In other words, you will perform your lab on Wednesday and have 2 days to make your lab report. Reports should be submitted in the marked box in the hallway outside the lab room. See the next section for instructions on preparing your lab reports.

LATE POLICY: Late labs get a 10% deduction per (business) day. Special arrangements can be made (in advance, whenever possible) for illness, emergencies, unavoidable absences, sports competitions, etc.

**LABORATORY COMPUTERS:** You may log on to laboratory computers using a lab username and password that will be given in class. Alternatively, you may use your ordinary Knox network username and password to log onto the lab computers - in that case, **be sure to log off before leaving the lab**.

viii

### PREPARING LABORATORY REPORTS

#### I. Report Format

Laboratory reports for this course will be very streamlined, since we want you to focus on understanding the physical ideas rather than on crafting extensive scientific reports. Your work should be clear and concise. The report you hand in should consist of the following parts:

#### 1. Identifying information:

- Your name
- "Lab partner:" followed by the names of your lab partner(s)
- Your lab time (Period 2, 3, or 5)
- 2. Answers to the questions including any necessary data analysis, calculations, and plots.
- 3. Raw data as an appendix, attached to the end.

No abstract, introduction, materials and methods, procedure, or conclusion sections are required in your lab reports this term.

#### II. Answers to Questions

Answer any question requiring an explanation concisely in good English. Whenever calculations are required, show them in full detail. Where calculations are required, you may either write the equations neatly by hand or format them properly (e.g. in Word using the Equation Editor). If a number of similar, repetitive calculations are necessary, show only one example.

#### When showing your calculations make sure you always:

- define all symbols used, e.g. m = mass of ball;  $v_o = initial$  speed of glider, etc.,
- **specify the units** of all measured quantities, including the slopes and intercept of plotted lines, unless they are unitless,
- take care to use a reasonable number of significant digits..

#### III. Raw Data

Present data cleanly and clearly. Whenever appropriate, present data in chart or tabular form. If you have handwritten raw data records, staple them to the back of your report as an appendix.

• Give your data tables a title so it is clear what the data refer to.

- Specify the units of measured quantities and take care to use a reasonable number of significant digits.
- When possible, estimate the uncertainty in a measured quantity. For example, if you are recording a length measurement of 0.500 m that you believe is accurate to within 2 mm, write:
   length of track = L = 0.500 ± 0.002 m.

### IV. Working Together

You are encouraged to work together on lab reports and may consult with anyone or any book that you may find helpful. However, **data may only be shared among lab partners who were** *both* **present when the data was taken.** You may not take data and share it with someone that was not there or request that someone do this for you - this is an Honor Code violation. Your final write-up must be your own unique product **typed by yourself without use of AI software or any other draft report to help you.** In particular, duplicate reports, even from lab partners, are not acceptable and will be viewed as a violation of the Honor Code.

Please feel free to consult me whenever I am in my office for help with any aspect of your laboratory experiment or report.

#### V. Experimental Accuracy

The experiments in this course generally give results that are accurate to better than  $\pm 10\%$  to the accepted values. If your experimental results differ form the expected values by significantly more, say 40%, then you likely have made an error in your calculations or a significant mistake in the lab procedure. In such a case, you should recheck your calculations or return to the laboratory and repeat the required measurements. The laboratory will be open ever weekday until 5PM or so, often later. You additionally have access by calling campus safety anytime.

#### VI. Preparing plots

All plots must be prepared using computer software such as Excel, Mathematica, or something similar. Plots must have a title and labels for the x- and y-axes, including the units of the plotted quantities. Do not connect the data points with line segments and do not attempt to draw a best fit line by eye. If the data set is linear, you should use a computer application (hopefully whatever you used to plot the data) to fit a straight line to your data similar to the process explained below for how to do so in Excel.

#### INSTRUCTIONS FOR PREPARING PLOTS USING EXCEL

- 1. Type or copy-and-paste data into columns in Excel.
- 2. Click-and-drag to select the data, then choose Insert, then click the Scatter Plot icon on the menu bar, then select the scatter plot with markers only from the drop-down menu.
- 3. With the plot selected, click the Layout tab under Chart Tools. You can then click appropriate icons to add a chart title and axis labels. Click Gridlines and select none to eliminate gridlines.
- 4. To add a linear regression or fit line to your plot, click Trendline, then More trendline options. In the popup dialog box, choose type Linear and check the boxes to Display equation on chart and Display R-squared value on chart. The R-squared value gives an indication of the linearity of your data; R-squared = 1 for perfectly linear data. Be sure to show sufficient digits so that the deviation of your value from 1 can be ascertained. Be sure to show a reasonable number of significant digits in the slope and *y*-intercept given on the plot. You can format the number of digits displayed by right-clicking on the trendline equation displayed on your graph and selecting the Format option.
- 5. Not all data is appropriate to apply a linear fit to. Make sure you are plotting data that you *expect* a linear relationship for before going through this procedure!!

#### CALCULATIONS IN EXCEL

Often in this course you will want to create a new data column containing values calculated using the values contained in other columns. You can, and should, do this in an automated way. When you click on a cell in Excel in the new column a formula bar should appear somewhere near the top of the window. In that formula bar is where you will want to enter the formula for whatever calculation you would like perform. Details on creating formulas can be found in the Help documentation in Excel, but a couple of simple examples are given below:

= A1\*2+1 (Doubles the value in cell A1 and adds one)
 = (A1^2+B1^2)^0.5 (Adds the squared values in cells A1 and B1 and takes the square root.)

Note that **formulas always start with the equals sign** =. After having typed a formula for one cell, you can copy-and-paste it into all similar cells (Excel automatically understands that it should use cells in the appropriate row for each calculation) by just clicking and dragging a box over all the appropriate cells.

### REPORTING MEASURED NUMBERS: SIGNIFICANT DIGITS

Reporting a measured number with an appropriate number of digits is important since any number published in a scientific report implicitly implies a certain experimental resolution. In other words, if you report a length of 1.045 mm, you are not just asserting the length, but also that your measuring device had a resolution of thousandths of a millimeter. So, if you display too many digits, you are making a misleading claim about the precision of your measurement.

Deciding how many digits are appropriate to report is not always simple - the Department of Physics and Astronomy covers the proper mathematical theory on this topic later in the courses PHYS 241 and PHYS 245. However, there is a very simple *approximate* way to do it: the method of "significant digits." Keeping track of the number of significant digits is quite easy to do and gets the number of digits about right ( $\pm 1$  digit), which keeps the experimental uncertainty to within about an order of magnitude (i.e. a factor of ten) of the correct value. Because it is simple and approximately right, the method is very worthwhile and all serious science students should get in the habit of keeping track of the number of significant digits in every reported number. Significant digits turns out to be both a useful and easy way to approximate our uncertainty.

#### NUMBER OF SIGNIFICANT DIGITS IN A MEASURED QUANTITY:

The number of significant digits in a measured number is determined by the resolution of the measuring equipment and by the magnitude of the quantity measured.

#### Examples:

A ruler with  $\pm 0.1$  mm precision is used to measure a one millimeter long sample. The result is: 1.0 mm  $\pm 0.1$  mm. (The quantity 1.0 mm has 2 significant digits).

The same ruler is used to measure a ten-centimeter long sample. The result is: 100.0 mm  $\pm$  0.1 mm (The quantity 100.0 mm has 4 significant digits).

Vernier calipers with  $\pm 0.05$  mm precision are used to measure the one millimeter sample. The result is: 1.00 mm  $\pm 0.05$  mm (The quantity 1.00 mm has 3 significant digits).

(Note that the uncertainty has only one significant digit – uncertainties are not accurately known quantities. Note also that the measured number has as many digits after the decimal point as the uncertainty so that they can be added.)

#### PROPAGATION OF SIGNIFICANT DIGITS IN A CALCULATION:

1. Adding/Subtracting

The number of significant digits in the result is determined by the operand with the least number of significant digits after the decimal point.

Examples:
2.005
0.04
+13.2415
15.29
1.954
- 0.43
1.52

2. Multiplying/Dividing or Other Operations (exponeniating, etc.)

The number of significant digits in the result is the same as the smallest number of significant digits in any of the operands.

#### Examples:

 $2.005 \times 1.04 \times (3.2 \times 10^2) = 6.7 \times 10^2$ 

(Note: Writing the above result as 670 is ok, but it is somewhat ambiguous whether or not the zero is supposed to be significant. The use of scientific notation avoids this ambiguity).

 $\sin(1.2\,\pi) = -0.59$ 

3. Using extra digits in intermediate steps of a calculation to avoid round-off error.

You may use an extra digit in intermediate steps to avoid error due to repeated round-offs. (Note that one or at most two extra digits is plenty; using all eight digits displayed by the calculator is always a waste of time).

If you use extra digits, this should be done in a part of your report designated for calculations. In the section of your report where you provide answers to the questions, the reported numerical values must have an appropriate number of significant digits.

### A BRIEF INTRODUCTION TO ERROR ANALYSIS

#### ERRORS AND UNCERTAINTIES

Suppose the theory you are testing predicts a value of 2.0 for a particular quantity, but your experimental value is 1.5. Is your experimental value consistent with the theory or not?

This sort of situation arises all the time with experiments: the measured number is not exactly identical with the predicted theoretical value. To draw any conclusion from the experiment, it's necessary to know what the precision of the measured number is. For example, if the measured number and its uncertainty are  $1.5 \pm 0.5$ , the measurement is consistent with the theoretical prediction of 2.0; however, if the measured number were  $1.5 \pm 0.1$ , it is not. Knowing the uncertainty in your measured number is an essential part of the experiment. The uncertainty number (the  $\pm 0.1$ ) is customarily called the "experimental error" although the term is somewhat misleading - no sort of error has necessarily been made by anyone - uncertainties are inherent in the measuring process due to the limitations of the instruments used and sometimes due to the statistical uncertainty inherent in the natural phenomenon itself.

#### TYPES OF ERRORS

It is important to realize that uncertainties can get into an experiment in a surprising number of different ways, and often just identifying the major source of uncertainty can be a challenge. The most obvious way uncertainties enter is through the limitations of the measuring instruments; for example, the smallest markings on the ruler are millimeters, so the uncertainty of a ruler measurement must be at least a millimeter. However, the uncertainty of a ruler measurement could easily be much more than a millimeter. Suppose you are measuring the focal length of a lens by focusing light from a distant source on a screen and measuring the lens-to-screen distance with a ruler. Different distances (maybe differing by a few mm) might look equally in focus to you, so the uncertainty in this case is a few mm. This is a *problem of definition* – the visual determination of "in focus" has uncertainty.

As another example, you might try measuring the length of a tabletop and find that you get slightly different measurements depending on what part of the table you measure – because its sides are not quite smooth or perhaps imperfectly parallel. Here again the uncertainty could be larger than the uncertainty coming from the ruler's markings. This uncertainty is due to **model** error: the model of the tabletop as rectangle is not exact.

Sometimes the way a measuring device is read contributes an error: if you are constrained to view the ruler from an angle rather than perpendicularly, the geometry of the viewing can result in *parallax error*.

Another possibility is that the ruler was manufactured poorly, with the markings 1% too close together – then all measurements made with this ruler will be low by 1%. This non-random error due to miscalibrated equipment, which is always present to some degree, is called *systematic error*. It can be difficult to estimate the size of systematic errors: sometimes the equipment

manufacturer specifies a probable or guaranteed maximum degree of systematic uncertainty in an equipment manual, sometimes an experimenter must undertake a separate *calibration experiment* to test the measuring instrument against a known standard (which itself has a specified maximum uncertainty, hopefully small).

Some uncertainties are actually *random*, and then the degree of uncertainty can be measured accurately by repeating the experiment many times – the degree of scatter among the measured values (i.e. standard deviation) can usually be taken as the measure of the uncertainty. In practice, however, uncertainties usually result from many sources – systematics, random uncertainties, and various model errors – and it is not always easy to figure out what source of uncertainty is dominant and which can be safely ignored.

As a last word on experimental error, it is important to understand that "human error" is **not** a legitimate type of experimental error. In other words, if you did a procedure wrong or wrote down a wrong number, **this does not count as "experimental error"** – it is simply a mistake. Note that the lab can be made available day and night, so if you should discover a mistake, you are encouraged to return and redo a procedure or an experiment.

#### ESTIMATING UNCERTAINTIES

As the above discussion indicates, figuring out the size of an experimental uncertainty can be tricky. Fortunately, we usually only require an estimate, and this is usually not too difficult. For ruler and other scale reading measurements,  $\pm$  half the smallest scale division is a reasonable estimate for the uncertainty (but be alert for situations where the actual uncertainty is larger, as in the examples above). This rough estimate will handle ruler and balance measurements. For timing measurements (including velocity), it is often convenient to repeat the measurement a few times - the maximum deviation from average gives a rough, order-of-magnitude measure of the uncertainty.

#### PROPAGATING UNCERTAINTIES

Once you know the uncertainties in the raw measured quantities in an experiment, you may still need to know the uncertainty in some other value calculated from the raw quantities. For example, after you measure the mass  $m \pm \Delta m$  and the volume  $V \pm \Delta V$  of an object, you might want to know the mass density and its uncertainty. Of course, the mass density  $\rho$  is given by  $\rho = \frac{m}{V}$  – but what is its uncertainty? This is the problem of *propagation of uncertainties* – figuring how uncertainties are affected when they propagate through a calculation or a series of calculations. There are well-established statistical rules for how to figure this out – but the rules are a little complicated and actually only rigorously valid for random uncertainties following the normal, or bell-curve, frequency distribution (although the method is *approximately* valid generally, and in practice used almost universally). We present instead a simpler approach for estimating the uncertainties in this course (which are usually dominated by systematic rather than random uncertainties): the uncertainty  $\Delta \rho$  in the density is given by

$$\Delta \rho = \frac{1}{2}(\rho_{\max} - \rho_{\min}),$$

where  $\rho_{\text{max}}$  is the maximum density consistent with the data and  $\rho_{\text{min}}$  is the minimum density. Hence we have

$$\rho_{\max} = \frac{m + \Delta m}{V - \Delta V} \quad \text{and} \quad \rho_{\min} = \frac{m - \Delta m}{V + \Delta V}.$$

Take a close look at the plus and minus signs in these relations and note that  $\rho_{\text{max}}$  is not the maximum mass over the maximum volume, but rather the maximum mass over the minimum volume.

The above approach to propagating uncertainties gives a *worst-case estimate*: the density reaches its limiting value  $\rho \pm \Delta \rho$  only when *both* mass and volume are at the (appropriate) ends of their respective ranges. If the uncertainties in mass and volume were random and uncorrelated, one might expect this event (both mass and volume simultaneously at the limit of their allowed ranges) to be rather unlikely, and the above procedure would then give an *overestimate* of the uncertainty. On the other hand, if the uncertainties in mass and volume are not random but due to systematic errors, we may in fact be most interested in this worst-case bound on the uncertainty. And as a practical matter, this estimate of the uncertainty will in most cases be not too much larger (say, within a factor of 2) than that calculated by the statistically rigorous approach. And in most cases, this degree of accuracy in the estimate of uncertainties is quite adequate – the calculation of uncertainties is sometimes not a very exact science! Thus, **it is always important to document how you calculated your uncertainties**.

#### Uncertainty in the Slope and y-intercept of a Linear Fit (Reference: J. Higbie, Am. J. Phys., Vol. 59, No. 2, February 1991)

Though the derivation goes beyond the scope of this class, one can calculate the uncertainty in the slope and y-intercept from the correlation parameters given to you in your linear fit.

• The uncertainty in the slope  $(\delta m)$  is given by:

$$\delta m = \frac{|m| \tan(\arccos(R))}{\sqrt{N-2}} \tag{1}$$

where m is the slope, R is the square root of the  $R^2$  value from the linear fit, and N is the number of data points in the data set. Note that there cannot be any uncertainty in the fit of you data if there are no more than 2 data points!

• The uncertainty in the y-intercept  $(\delta b)$  is given by:

$$\delta b = \delta m \cdot x_{\rm rms} \tag{2}$$

where  $x_{\rm rms}$  is the root mean square value of the x values.

• The root mean square value of a set of x values can be found as

$$x_{\rm rms} = \sqrt{\frac{1}{N} \left(\sum_{i=1}^{N} x_i^2\right)} \tag{3}$$

As you can see, it is the "root" of the "mean" of the "squares". Note that, the further the values are from the y-axis the larger the  $x_{\rm rms}$  value and consequently the larger the uncertainty in the y-intercept for a given slope uncertainty.

#### **Further Reading**

Students interested in further reading on the subject of error analysis are directed to John Taylor's excellent and highly accessible text An Introduction to Error Analysis.

### A BRIEF INTRODUCTION TO LINEAR INTERPOLATION

It is expected that students bring with the to this course a familiarity with linear equations. In the common 'slope-intercept form" y = mx + b where m is the slope and b is the y-intercept. Recall that given two points on a line, the equation for the line can be determined. The slope is found from  $m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x}$ . Using the calculated slope, one can find the y-intercept by plugging in one of the two given points and solving for the unknown intercept b.

In this course, we will often deal with functions that are not linear. However, the vast majority of the functions we will encounter will be continuous and smooth. When you zoom in on a smooth continuous function f(x) and consider how the function is changing between two values of x (e.g.  $x_1$  and  $x_2$ ) where  $\Delta x$  is sufficiently small, the points of the function between  $x_1$  and  $x_2$ can be approximated with a linear function defined by the points  $(x_1, y_1)$  and  $(x_2, y_2)$  in the usual manner. Now this approximation is only appropriate for values of x between  $x_1$  and  $x_2$ . For a different interval, a different linear function must be determined.

EXAMPLE: Consider Table 1 in Lab 1 which has Temperature vs. Resistance for the thermistor we are using. Suppose you measure a resistance for the thermistor of 200,000  $\Omega$ . To what temperature does this resistance correspond?

- 1. Note that the resistance measurement falls in the interval between points (207,850  $\Omega$ , 10°C) and (197,560  $\Omega$ , 11°C).
- 2. To find the linear interpolation equation we'll first determine the slope:

$$m = \frac{\Delta y}{\Delta x} = \frac{\Delta T}{\Delta R} = \frac{T_2 - T_1}{R_2 - R_1} = \frac{11^{\circ}\text{C} - 10^{\circ}\text{C}}{197560\Omega - 207850\Omega} = -9.718 \times 10^{-5} \frac{^{\circ}\text{C}}{\Omega}$$

3. Now by subbing one of our points into an equation using the above slope we get

$$y = mx + b \to 10 = (-9.718 \times 10^{-5} \frac{\text{°C}}{\Omega}) * (207,850\Omega) + b$$

This yields  $b = 30.20^{\circ}$ C

4. We can now determine the temperature that corresponds to the resistance we measured.

$$T = mR + b = (-9.718 \times 10^{-5} \frac{^{\circ}\text{C}}{\Omega}) * (200,000\Omega) + 30.20^{\circ}\text{C} = 10.76^{\circ}\text{C}$$

Note the reasonableness of this answer. Not only does it fall in our range, but it is closer to 11°C as one would expect based on resistance.

### PHYSICS 120 - EXPERIMENT 1 THERMAL EXPANSION OF METALS

### 1 Introduction

Most materials expand when heated and contract when cooled. From experiments on rods and wires, it is found that the fractional change in length is usually proportional to the change in temperature, a relation that can be expressed concisely as

$$\frac{\Delta L}{L} = \alpha \Delta T \tag{1}$$

where L is the original length,  $\Delta L$  is the change in length (i.e. final length minus initial length), and  $\Delta T$  is the change in temperature (i.e. final temperature minus initial temperature). The symbol  $\alpha$  is a temperature-independent constant of proportionality called the **thermal coefficient of linear expansion**.

The interesting physical content of Eq. (1) is contained in

- the numerical value of  $\alpha$ , which depends on the type of material
- the sign of  $\alpha$ , which is positive for materials that expand when heated (See Giancoli 17-4 for more details).

It is a challenging problem in solid-state physics and beyond the scope of this course to predict  $\alpha$ , which could only be done from quantum mechanical theory and from knowledge of the crystal structure of a particular material. However, it is a test of any theory to compare predictions with experimental measurements and our goal in this experiment will be to measure  $\alpha$  for several different metal rods and compare those with expected values.



Figure 1: Diagram of the thermal expansion apparatus.

### 2 Procedure

The parts of the apparatus described in this section are illustrated in Figure 1 on the previous page.

- 1. Carefully measure the distance between the black lock-rings mounted on the copper, aluminum, and brass rods using a meterstick. Record these values and their respective uncertainties in the table at the end of this handout. Minimize handling the metal rod with your hands so that it remains at room temperature.
- 2. Insert your metal tube in the apparatus. First, slip the smaller lock-ring into the slotted mounting block at the opposite end from the dial indicator. You may have to loosen the silver set screw to allow the lock-ring to slip into its slot. When it does, *gently* tighten the set screw. The larger lock-ring should be in contact with the spring-loaded arm of the dial indicator–you will need to *gently* push back the movable pointer of the dial indicator to allow the sample rod to slip into place. The sample rod should now be sitting securely in the apparatus, with the smaller lock-ring fixed in position by the set screw and the larger lock-ring resting against the movable pointer of the dial indicator, so that the dial will measure the expansion of the tube.



Figure 2: Dial indicator, movable pointer, and lock-ring.

- 3. Connect the thermistor jack into its socket near the sample rod end opposite the dial indicator.
- 4. Connect the digital multimeter to the terminals on the apparatus below the thermistor jack. On the multimeter, use the terminals labeled COM and  $V/\Omega$  and set the rotary switch for the 200 k $\Omega$  range during the experiment, try lower ranges and use the lowest (most sensitive) range that gives a reading. Record the reading, which will be a resistance in k $\Omega$ , and its

uncertainty. Assume the meter's uncertainty is  $\pm 0.5\%$  plus  $\pm 1$  in the last digit. You can convert the reading into a temperature in °C using the calibration chart below (the same chart is provided on a card attached to the apparatus). Use linear interpolation to convert the resistance reading to a temperature value, reporting your temperature to the nearest tenth of a degree. Assume the temperature measurement uncertainty is  $\pm 0.3$  °C.

- 5. If needed, fill the reservoir of your steam generator with water from the tap, and connect the rubber hose to your metal tube. Position a cup to catch condensed hot water at the end of the tube.
- 6. Push the center ON/OFF button on the dial indicator to power it on, then the ZERO button. Check that the display is reading in millimeters (there is an in/mm button if needed.) Do not touch or bump the apparatus again until the experiment is over the dial indicator reads in 0.01 mm of displacement and is sensitive to small bumps.
- 7. Wait until the water is boiling and steam is coming out of the tube. **Be extremely careful** to keep away from the steam output. Wait several minutes for the temperature reading to stabilize you'll probably need to change to a more sensitive scale on the multimeter. When the reading is stable, record the final temperature and the final dial indicator reading and turn off the heat.

Wait about 5 minutes for the parts to cool before attempting to disconnect the steam hose and disassembling the apparatus to prepare for the next experiment.

8. Do a quick calculation of the thermal expansion of your metal rod and check how it compares to the expected value (see Question 3). If you have extra time, your precision can be improved by repeating the experiment and averaging the results.

#### Thermistor Conversion Table

Temperature Versus Resistance

тні	ERMIST	OR: TEM	PERATI	JRE VER	SUS RE	SISTANC	E
55,142 9 52,235 49,499 46,924 44,500 42,215 40,057 38,025 36,107 34,298 32,590 30,974 29,448 28,007	2 -10 °C -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3	26,645 25,357 24,138 22,984 21,892 20,858 19,880 18,953 18,074 17,242 16,452 16,452 16,452 14,992 14,317	<ul> <li>Ω 4 °C</li> <li>5</li> <li>6</li> <li>7</li> <li>8</li> <li>9</li> <li>10</li> <li>11</li> <li>12</li> <li>13</li> <li>14</li> <li>15</li> <li>16</li> <li>17</li> </ul>	13,676 9 13,068 12,491 11,941 11,418 10,921 10,450 10,000 9,572 9,166 8,778 8,409 8,058 7,724	2 18 °C 19 20 21 22 23 24 25 26 27 28 29 30 31	7,405 Ω           7,100           6,810           6,534           6,271           6,019           5,778           5,549           5,329           5,120           4,920           4,729           4,371	32 °C 33 34 35 36 37 38 39 40 41 42 43 44 45
646-15339							
4,204 Ω 4,045 3,892 3,745 3,601 3,471 3,342 3,219 3,101 2,988 2,880 2,776 2,677	46 °C 47 48 49 50 51 52 53 54 55 56 57 58	2,489 Ω 2,401 2,317 2,236 2,158 2,084 2,012 1,942 1,877 1,814 1,753 1,694 1,637	60 °C 61 62 63 64 65 66 67 68 69 70 71 72	1,531 Ω 1,480 1,432 1,386 1,341 1,298 1,256 1,216 1,178 1,141 1,105 1,071 1,038	74 °C 75 76 77 78 79 80 81 82 83 84 85 86	975         Ω           945         917           989         862           837         812           788         765           742         721           700         680	88 °C 89 90 91 92 93 94 95 96 97 97 98 99 99 100

### 3 Questions

1. Suppose that a student, Cal I. Brator, is performing the thermal expansion experiment and obtains the following data for their aluminum rod sample: initial length =  $35.00 \pm 0.03$  cm change in length =  $0.63 \pm 0.01$  mm initial temperature =  $23.0 \pm 0.3^{\circ}$ C final temperature =  $94.0 \pm 0.3^{\circ}$ C.

(Writing that the measured length was  $35.00 \pm 0.03$  cm means that the actual length may be as low as 34.97 cm or as high as 35.03 cm or any value in between.)

- (a) Ignoring uncertainties, calculate the value of  $\alpha$  from Cal's data.
- (b) Taking uncertainties into account, calculate the largest possible value of  $\alpha$  consistent with Cal's data and also the smallest possible value of  $\alpha$ . Show all your calculations.
- (c) Report Cal's answer for  $\alpha$  in the form  $X \pm Y$ , where X is the value you found in (a) and Y is the uncertainty in your calculation taken to be  $Y = (\alpha_{max} \alpha_{min})/2$ .
- (d) Using linear interpolation (see page xix), determine the temperature corresponding to a measured resistance of 13,000  $\Omega$ .

- 2. Calculation: Using your data, calculate the thermal coefficients of linear expansion for (i) copper, (ii) brass, and (iii) aluminum. Give numerical values and proper units, and fully show and explain your calculations. In this part, you only need to calculate  $\alpha$ , not its uncertainty.
- 3. Percent Error: The CRC Handbook of Chemistry and Physics gives the following values for the thermal expansion coefficients:  $\alpha_{Al} = 23.4 \times 10^{-6} \,^{\circ}\text{C}^{-1}$ ,  $\alpha_{Cu} = 16.6 \times 10^{-6} \,^{\circ}\text{C}^{-1}$ , and  $\alpha_{Br} = 18.7 \times 10^{-6} \,^{\circ}\text{C}^{-1}$ . Calculate the percent errors in your measured values, taking the CRC data as the "accepted values." Recall that percent error is given by

% error = (measured value - accepted value)/(accepted value)  $\times$  100%.

When you report percent error, do not use an unreasonable number of non-significant digits - typically, one reports one digit for percent error (at most two digits).

- 4. Uncertainty: Calculate and report the uncertainty for your results in the manner described in Question 1. It is sufficient to show your calculations in detail for just one of the samples, but report your results (in the form  $value \pm uncertainty$ ) for all of the samples.
- 5. Consistent Results: Do your measurements agree with the accepted values? (Important Note: A measured value is generally said to agree with an accepted value if the difference is within twice the uncertainty.)
- 6. Systematic error: Our current estimation of the uncertainty may not have accounted for all types of uncertainty. Returning to Question 1: Suppose the rod in Cal's experiment initially (i.e. when he placed it in the steam tube) had a temperature a few degrees above room temperature (say 27.0°C), but Cal incorrectly assumed that the rod was at room temperature (say 23.0°C). Ignore all sources of experimental error other than this improper calibration of the initial temperature in Cal's measurements for this question.
  - (a) Will Cal's reported value of  $\alpha$  to be too high or too low?
  - (b) What percent error will result from this mistake?

Be sure that you have read **GUIDELINES FOR PREPARING LABORATORY REPORTS** before completing and handing in your lab report.

Rod	Initial $L$ (cm)	$\Delta L (mm)$	Initial $T$ (° $C$ )	Final $T$ (°C)
Aluminum				
Copper				
Brass				

### PHYSICS 120 - EXPERIMENT 2 Ideal Gases: Laws of Boyle and Gay-Lussac

### 1 Introduction

At room temperature and atmospheric pressure, air molecules (primarily nitrogen and oxygen) are widely separated and interact very weakly with each other. The physical properties of air (or any gas) under these conditions can be predicted accurately even when neglecting the weak interactions between molecules and imagining an *ideal* gas of point-like particles that whose motions are perfectly independent, unaffected by the motions of the other particles. This *ideal gas* model is very useful for describing most gases over a wide range of pressure and temperature.

The equation of state of an ideal gas, usually called the **ideal gas law**, was not discovered in its current well-known form PV = nRT. Instead, binary relationships between each pair of variables P, V, and T were found first and are named after their discoverers. Robert Boyle (1627-1691) observed that pressure of a gas varies inversely with the volume; Jacques Charles (1746-1823) observed a linear relation between the volume and temperature of an ideal gas; and the picture was completed when Joseph Gay-Lussac (1778-1850) observed a linear pressure-temperature relationship. In this experiment, we will work to duplicate both Boyle's and Gay-Lussac's findings and use these results to determine the zero point of absolute temperature or what is commonly known as **absolute zero**.

### 2 Procedure

#### I. BOYLE'S LAW EXPERIMENT:

In this experiment we will investigate the relationship between pressure and volume. We will require a thermistor, a syringe piston, a pressure sensor, and a PC running LoggerPro. Confirm that the pressure sensor and thermistor are plugged into channels 1 and 2 of the LabPro device and reading properly.

- 1. Measure and record room temperature with the thermistor.
- 2. Adjust the syringe piston so that it reads 10.0 cc (cubic centimeters). Make sure the valve on the pressure sensor is open (the plastic handle should be parallel to the tubing connecting the pressure sensor and the syringe). Connect the syringe to the pressure sensor by carefully twisting the plastic luer-lock connector on the tubing from the sensor onto the syringe tip.
- 3. Set the pressure units to kPa and temperature to Celsius. Since the pressure should be room pressure with the piston at 10 cc, the reading should be near (but probably not exactly) 1 atm.
- 4. Carefully pull the syringe piston out to the 20 cc mark. Record the pressure, and then advance the piston position in 2 cc steps in to the 6 cc mark. Make sure you record the pressure at each piston position. Then, take one more reading with the piston

at the 5 cc mark. Do not advance the piston beyond the 5 cc mark, as this may result in damage to the pressure sensor. Try to perform this relatively quick as this will lessen the risk of a slow leak of air past the piston and compromised data (due to systematic error from the leak).

#### II. GAY-LUSSAC'S LAW EXPERIMENT:

In this experiment we will investigate the relationship between pressure and temperature. We will require an electrically heated water bath, copper chamber, mounting clamp, pressure and temperature sensors, and PC running LoggerPro.



Figure 1: Apparatus for the Gay-Lussac Law Experiment

- 1. Fill the reservoir in your water bath about half full of water at room temperature, so that the copper chamber can be mostly immersed without the reservoir overflowing. Keep the rubber tubing above the level of the water in the bath. Adjust the mounting clamp to hold the copper chamber in the water bath. Make certain that the copper chamber is **not** in contact with the bottom or the walls of the reservoir.
- 2. When the copper chamber is in position, check that the thermistor sensor and the pressure sensor are connected to the LabPro interface and set up the Logger Pro software to record the temperature and pressure. To do this choose Experiment  $\rightarrow$  Data Collection, then configure the software to acquire data at 5 second intervals and check the continuous data collection box. Place the thermistor in the water bath next to the copper chamber.
- 3. Turn on the heater with the heating power set around 60% of maximum and click start to begin acquiring data. Gently stir the water bath with the thermistor sensor to minimize temperature gradients in the bath and maintain continual gentle stirring throughout the experiment. Avoid contacting the metal walls of the reservoir with the thermistor to ensure that it accurately reads the water temperature.
- 4. When the bath temperature reaches 90°C, stop data collection and turn off the water heater.

5. To plot or analyze your data, you can transfer your LoggerPro data to another program like Excel by simply selecting (highlighting) your data, copying (Ctrl-C) from LoggerPro, and then pasting (Ctrl-V) in Excel.

### 3 Questions

#### 1. Boyle's Law:

- (a) Starting with the ideal gas law, derive algebraic expressions for the slope and y-intercept of a plot of pressure P vs. inverse volume  $V^{-1}$  of a gas, in terms of the constants n, R, and/or T, where T is the temperature in Kelvin. (Recall that a plot of A vs. B means that A is on the y-axis and B is on the x-axis.)
- (b) Plot your data for the Boyle's Law experiment, P vs.  $\frac{1}{V}$ . Use standard metric (MKS) units. Use plotting software such as Excel to fit a straight line through your data. Is your plot consistent with Boyle's Law? Explain briefly.
- (c) Making use of the slope from best-fit line, calculate the total number of gas molecules (N) confined in the piston in your experiment. Show your work and explain your reasoning clearly.
- (d) What is the uncertainty in your value for N? (**Hint:** You will need to again consult the parameters from your best-fit line and read over the page "Uncertainty in the slope and *y*-intercept of a linear fit" on page xviii.)
- (e) Report your result for the number of gas particles in the piston in your experiment complete with uncertainty in the form  $N \pm \delta N$ , using the proper number of significant figures for N and its uncertainty  $\delta N$ .

#### 2. Boyle's Law II:

Suppose room temperature increases during the Boyle's Law experiment (assume the gas in the syringe remains in thermal equilibrium with the room at all times). Sketch how the plot in Question 1(a) would be effected. If the change is small so the plot still approximately resembles a line, does the measured slope increase, decrease, or remain the same? Explain.

#### 3. Gay-Lussac Law:

- (a) Start with the ideal gas law in the form  $PV = nR(T_0 + T)$ , where  $T_0$  is an unknown quantity with units of degrees Celsius and T is the temperature in degrees Celsius. Derive algebraic expressions for the slope and y-intercept of a plot of temperature T (°C) vs. pressure P. Express your answers in terms of the constants n, R, V, and/or  $T_0$ .
- (b) Plot your data for the Gay-Lussac Law experiment, T (in °C) vs. P (in N/m<sup>2</sup>). Check if your plot supports the Gay-Lussac Law, which predicts that temperature is proportional to pressure for a fixed volume of gas. Check proportionality by fitting with a straight line and considering the quality of the fit. Comment on if your results confirm the

Gay-Lussac Law and how well they seem to support the expected proportionality. Be as quantitative as possible.

- (c)  $T_0$  is the zero point of *absolute* temperature in degrees Celsius. Using the expressions for slope and intercept you derived above and the numerical values of the slope and intercept from the best-fit line on your plot, find the value of  $T_0$  predicted from your measurements.
- (d) Determine the uncertainty  $(\delta T_0)$  on your value for absolute zero. Again, see page xviii. Express your result for  $T_0$  in the form  $T_0 \pm \delta T_0$  with units and an appropriate number of significant digits. Does your result agree with the expected value? Is your result consistent within the range of uncertainty or is some significant error present? Explain, and again be quantitative whenever possible.

#### 4. Systematic Uncertainty:

- (a) What would your data look like if you failed to ensure that the gas remained at the same temperature as the water (i.e. the gas warmed more slowly than the water)? Sketch a rough plot of the hypothetical data. (Don't just do this without thinking, take some time and think about it and explain your reasoning.)
- (b) What effect would this have on your determination of absolute zero? (Think about your answer to part (a) as that should help you visualize.)

#### 5. Ideal Gas Law:

The ideal gas law predicts the behavior of most real gases over a large range of conditions quite accurately. What does this fact suggest about the validity of ignoring interactions between molecules in a real gas?

### PHYSICS 120 - EXPERIMENT 3 Specific Heat of Metals

#### 1 Introduction

When an object is warmed, heat flows into the object (Q > 0) and its thermal energy increases  $(U_{th} > 0)$ . Similarly, when an object cools, the object loses thermal energy  $(U_{th} < 0)$  as heat flows from the object (Q < 0). The heat flow Q is proportional to the object's mass m and to the change in temperature  $\Delta T$ , given by

$$Q = mc\Delta T \tag{1}$$

where c is a proportionality constant called the **specific heat** and has units  $\frac{\text{cal}}{\text{g}^{\circ}\text{C}}$ . The value of c depends only on the type of material under investigation and is independent of mass and approximately independent of temperature. One can interpret the specific heat (c) as the quantity of heat required to raise the temperature of one gram of material by one degree Celsius. The energy unit of a calorie (cal) is related to a Joule by 1 cal = 4.184 J.

When two objects at different temperatures are placed in thermal contact, the objects exchange energy and come to thermal equilibrium at an intermediate temperature. Said another way, heat (Q) will flow from one object to another so long as there is a difference in temperatures (i.e. a temperature gradient). If the objects (A and B) are isolated from their surroundings, then we would expect energy to be conserved and thus the *total change* of thermal energy for the *system* (A and B) should be zero:

$$\Delta U_{system} = \Delta U_A + \Delta U_B = Q_A + Q_B = 0 \tag{2}$$

which implies that

$$\Delta U_A = -\Delta U_B, \text{ or equivalently } Q_A = -Q_B \tag{3}$$

This means the heat that flows from object A is equal to the heat that flows into object B.

If the objects are thermally isolated from their surroundings in an apparatus called a **calorimeter** and the temperature changes are measured accurately, the experiment can be used to gain information about the thermal energy storage capacity, or **heat capacity**, of the objects.

We will measure the specific heats of samples of pure aluminum, copper, and lead using **calorime-try**:

- Each metal sample will be heated to a known initial temperature and placed into a known quantity of water at a measured initial temperature.
- After thermal equilibrium is reached, the final temperature of the water/metal system can be measured.
- The specific heat of water is exactly 1  $\frac{\text{cal}}{\text{g}^{\circ}\text{C}}$  (this actually serves as the **definition of the** calorie).

• The calorimeter apparatus used is basically a closed Styrofoam cup which provides excellent thermal isolation and has negligible heat capacity.

### 2 Procedure

- 1. Fill the reservoir of your electrically heated water bath to a level 2 cm below the top. The optimum water level is even with the lower edge of the embossed ring near the top of the reservoir. Check that the sample cup (dipper) fits into the top lid of the reservoir without causing the bath to overflow. Then turn on the bath with the power level set on maximum.
- 2. Dry your sample cup, then weigh it on the triple beam balance. Next, fill the sample cup with the aluminum sample material and weigh again to determine the mass of the aluminum. Place the tip of a glass thermometer in (or near) the aluminum shot. Then place the sample cup in the aperture in the lid of the water bath, so that the aluminum is in good thermal contact with the bath. Wait until the aluminum shot has reached a constant temperature. This may take around 10 minutes and should be approximately 90°C.



- 3. Carefully blot dry your Styrofoam calorimeter and weigh it on the triple beam balance. Wait until your metal shot in the boiling cup is hot enough before proceeding to the next step.
- 4. Add roughly 60 mL of water to your calorimeter cup. Optimally, the water should be several degrees cooler than room temperature, although this is not crucial. Carefully dry the outside or lip of your calorimeter cup to remove any external drops of water. Weigh the cup+water to determine the water mass. Cover the calorimeter, insert the thermistor probe through the access hole in the top cup, and measure the initial temperature of the water. Logger Pro should allow you to measure this temperature to 0.1°C precision.
- 5. Note and record the temperature of the metal shot in the flask. Using gloves or a towel to protect your hands, remove the stopper with the mercury thermometer, the flask from the boiler, then quickly blot the bottom dry and transfer the metal shot to your calorimeter without splashing any water out. Immediately replace the top cover of the calorimeter and gently swirl the contents for about 30 seconds so the metal and the water reach thermal equilibrium. Then, insert the thermistor probe through the access hole and measure the temperature of the water in the calorimeter. (If you wait awhile, you may observe a slow decrease in the water temperature as the calorimeter contents cool to room temperature.)

- 6. When finished, carefully decant the water from the calorimeter into a waste vessel. Then carefully transfer the shot onto some paper towels and blot dry. Once dry, use a funnel to replace the shot in its storage bottle.
- 7. Repeat the procedure for the aluminum, copper, and lead samples. As usual, if time allows, you can improve your accuracy by repeating trials and averaging results.

### 3 Questions

- 1. Using your data, calculate the specific heats of copper, aluminum, and lead. Show your results and a sample calculation.
- 2. The CRC Handbook of Chemistry and Physics gives the following values for the specific heats: 0.031 (Pb), 0.215 (Al), 0.092 (Cu) in units of  $\frac{cal}{g^{\circ}C}$ . Calculate the percent error from these accepted values for the values you found.
- 3. For lead, find the maximum range of uncertainty in your measurement. Report your answer in the form: value  $\pm$  uncertainty, with an appropriate number of significant digits and proper units. Show your calculation. Does your error fall within this range of uncertainty?
- 4. Do the errors found in question 2 appear to be *random* or *systematic*? Explain your reasoning.
- 5. Suppose a small quantity of water at  $100^{\circ}$ C were carried over with the metal sample and deposited in the calorimeter. Would this cause a measured value of c that is too low or too high? Explain.
- 6. The product mc is called the *heat capacity* and denoted C. What is the *heat capacity* of each of the three metal shot samples you measured?
- 7. Suppose a 2.00-kg mass of lead at 99.0°C with a specific heat of 0.031  $\frac{\text{cal}}{\text{g}^{\circ}\text{C}}$  is dropped in a well insulated cooler with 10.0 liters of water at a temperature of 10.0°C. What is the equilibrium temperature?
- 8. Suppose a 1.00-kg mass of lead at 99.0°C with a specific heat of 0.031  $\frac{\text{cal}}{\text{g}^{\circ}\text{C}}$  is dropped in a lake. How much heat will flow from the lead if the lake temperature is 10.0°C? (Do we need to know how much the lake warmed to solve this problem? If not, why not?)

### PHYSICS 120 - EXPERIMENT 4 LATENT HEAT OF FUSION AND VAPORIZATION

#### 1 Introduction

Consider a sample of ice that is being warmed by some source.

- When the sample of ice is warmed, its temperature increases as it heat (Q) flows into it and its thermal energy increases  $(\Delta U_{th} > 0)$ , until it begins to melt at 0°C.
- At that point, the sample temperature does not increase while heat is added to the system; instead, the ice in the sample gradually melts to water at 0°C as the thermal energy continues to increase.
- Increasing the rate of heat transfer to the ice-water system does not increase its temperature but instead increases the melting rate of the ice.

When we encounter this phenomenon we are encountering the phenomenon known as **latent heat** where additional heat must be added or removed from a material in order for it to undergo a phase transition.

• The amount of heat (Q) needed to melt a given sample of ice depends only on the mass m of ice and is given by

$$Q = mL_f \tag{1}$$

where  $L_f$  is a constant called the **latent heat of fusion** of ice. If we continue to add heat to the water after the ice has melted, its temperature increases in accordance with the relation

$$Q = mc\Delta T \tag{2}$$

as we observed last week (where c is the specific heat of liquid water).

- Once the water begins boiling (at 100°Cat 1.00 atm of pressure), further addition of heat does not increase its temperature; instead, the water sample continues to boil and to form steam.
- Again, increasing the rate of heating does not change the temperature but instead increases the rate of conversion of the liquid to gas.
- The quantity of heat Q required to convert a mass m of water to steam at the boiling temperature is given by

$$Q = mL_v \tag{3}$$

where  $L_v$  is a constant called the **latent heat of vaporization**. One can interpret the latent heat of vaporization as the energy difference (per unit mass) between steam and water: the water molecules in steam have a considerably higher average velocity, hence more kinetic energy per molecule, than the molecules in liquid water and thus a greater thermal energy.

The **latent heats of fusion and vaporization** are material-dependent constants having different values for different substances. In this experiment, we will use calorimetry to measure the latent heats of fusion and vaporization of water.

### 2 Procedure

#### 2.1 Latent Heat of Vaporization

- 1. Fill the reservoir of your electric steam generator, put the lid in place, and check that the rubber tubing is securely connected from the output port of the steam generator and to the water trap. If necessary, drain excess water from your water trap (the lab instructor can assist with this). Then turn on your heater and set the power level to maximum.
- 2. Gently blot dry (if necessary) and then weigh your Styrofoam calorimeter (both sections together). Use the electronic balance for best accuracy; check that the readout is in units of grams.
- 3. Fill the calorimeter with approximately 100 mL of water near room temperature. Weigh the filled calorimeter to find the water mass, using the electronic balance. Insert the thermistor probe in the calorimeter and determine the initial temperature. Wait until steam is being copiously produced from the output port of your water trap before proceeding.
- 4. Remove the thermistor and insert the steam tube (from the output of the water trap) into your calorimeter so that it is below the level of the water. Allow steam to flow into your calorimeter for about 60 seconds, until the water temperature has risen at least 10-20°C. After this time, remove the steam tube, gently swirl the contents of your calorimeter so that it reaches thermal equilibrium, and measure the temperature with the thermistor. If the temperature has not increased by at least 10°C, re-insert the steam tube to introduce more steam.



5. After recording the final calorimeter temperature, weigh the filled calorimeter again on the electronic balance to determine the mass of the condensed steam that has been added to the system.

#### 2.2 Latent Heat of Fusion of Ice

- 1. Fill the calorimeter with about 100 mL of water, approximately 5 or 10°C above room temperature. Use an ordinary triple beam balance to determine the water's mass. Insert the thermistor and find the initial temperature.
- 2. Blot dry several pieces of ice (about 2-3 cubes worth or 20 g) using paper towels and add them to the calorimeter. Avoid splashing out any water and avoid touching the ice with your hands.
- 3. Gently swirl the calorimeter for 30 seconds or so until the ice melts. Insert the thermistor probe and measure the minimum temperature attained. (If you wait, you will observe the calorimeter contents slowly warming to room temperature.)
- 4. Weigh the filled calorimeter to determine the mass of the added ice.

### 3 Questions

- 1. Suppose your data for the latent heat of vaporization experiment were: initial water temperature =  $19.50^{\circ}$ C, final water temperature =  $41.20^{\circ}$ C, initial water mass = 65.10 g, final water mass = 67.30 g.
  - (a) Present an algebraic expression for the latent heat of vaporization  $(L_V)$ .
  - (b) What is the latent heat of vaporization  $L_V$  (in  $\frac{\text{cal}}{\text{g}}$ ) based on the data given here?
  - (c) What is the percent error from the standard (accepted) value of the latent heat of vaporization given in your textbook? Show your calculations.
- 2. Calculate the latent heat of vaporization  $(L_V)$  of water from your data. Report your result and its uncertainty; give your result in the form  $L_V \pm \delta L_V$  with appropriate number of significant figures. Show all your calculations.
- 3. Look up the accepted value for the latent heat of vaporization and calculate the percent error for your value in Question 2.
- 4. Is your measurement consistent with the accepted value? Explain. (Again recall that it is generally considered to be "in agreement" if your result is within twice the uncertainty.)
- 5. Calculate the latent heat of fusion  $(L_F)$  of water from your data. Report your result and its uncertainty; give your result in the form  $L_F \pm \delta L_F$  with appropriate number of significant figures. Show all your calculations.

#### 6. Systematic Error:

- (a) What is the function of the glass water trap?
- (b) Suppose your data for the Latent Heat of Vaporization experiment were the same as those in Question 1: initial water temperature =  $19.50^{\circ}$ C, final water temperature =  $41.20^{\circ}$ C, initial water mass = 65.10 g, final water mass = 67.30 g. If 0.10 g of the incoming steam condensed in the output tube of the water trap and dripped into your calorimeter (assume the drops are at  $100.00^{\circ}$ C), what percent error would result due to this oversight ("error" in this case is the % deviation from the calculated result, not the accepted value)? Would your value of  $L_V$  be too high or too low?
- 7. Suppose that after your initial weighing of the perfectly dry calorimeter, a small drop of water, unnoticed by you, splashed onto and adhered to the outer wall of the calorimeter during the entire Latent Heat of Fusion experiment, remaining at its initial temperature. Would your value of  $L_F$  be too high or too low? Explain.

### PHYSICS 120 - EXPERIMENT 5 SIMPLE HARMONIC OSCILLATIONS OF A MASS-SPRING SYSTEM

#### 1 Introduction

Simple harmonic oscillation is one of the most important topics in physics for two reasons. First, oscillations give rise to waves, and many interesting physical phenomena are wave phenomena–including sound, light, and even the structure of atoms (described by the theory of quantum mechanics). Second, simple harmonic oscillations *are* relatively simple to understand, and an elegant mathematical result called Fourier's Theorem allows us to express arbitrary non-simple oscillations of a system as a superposition of simple harmonic oscillations. This interesting subject is explored further in later physics courses.

The simplest simple harmonic oscillator (SHO) consists of a mass m coupled to a spring with **spring constant** k, sliding on a frictionless surface (see Fig. 1). Suppose the mass is displaced by a distance x from the equilibrium point  $x_{eq}$  (where the spring is neither stretched nor compressed). The stretched spring then pulls the mass back toward equilibrium with a force  $F = -k(x - x_{eq})$  or F = -kx if we choose the equilibrium position to be the origin of our coordinate system  $(x_{eq}=0)$ .

Newton's second law gives  $F_{net} = ma$  for the force on the mass, where a is the acceleration of the mass m. Thus, we have

$$ma = -kx. (1)$$

Dividing by the mass m, we have

$$a = -\frac{k}{m}x = -\omega^2 x \tag{2}$$

in which we have defined a new symbol  $\omega = \sqrt{\frac{k}{m}}$ , which is called the **angular frequency**.

We see that since  $\omega^2 > 0$ , whenever x is positive, the acceleration (a) will be negative. Whenever x is negative, a will be positive. In other words, whenever the spring is stretched, the mass is accelerated in the negative direction toward the equilibrium point. Conversely, whenever the spring is compressed the mass is accelerated in the positive direction, again toward the equilibrium point.



Figure 1: A simple harmonic oscillator. The elastic constant of the spring is k, the mass is m, and x denotes the displacement of the mass from its equilibrium position at x = 0. At the equilibrium point, the spring is neither stretched nor compressed.

Since the mass arrives at the equilibrium point with some velocity, it overshoots the equilibrium point, thus repeating the process and producing oscillations.

Equation (2), which relates the position and acceleration of the mass, is called the equation of motion and has the general solution

$$x(t) = A\cos(\omega t + \phi), \tag{3}$$

where A and  $\phi$  are constants depending on the initial conditions of the systems when it is initially set in motion. A is called the amplitude of the oscillation; it is the maximum displacement from the equilibrium point the mass attains. The constant  $\phi$  is called the phase constant and indicates the mass's relative position at the starting time.

Using calculus, it is easy to substitute expression (3) into Eq. (2) and, by recognizing that the acceleration is the second derivative of position with respect to time  $(a = \frac{d^2x}{dt^2})$ , you can show that expression (3) satisfies the equation of motion. Those that are not familiar with using calculus must content themselves with the qualitative argument, and the plausible reasoning that oscillations of the mass ought to be described by an oscillating function such as cosine.

In this week's lab, we will investigate oscillations in a mass-spring system. We will explore the dependence of the oscillation period on the mass and elastic constant of the spring. Also, we will explore some interesting behavior of a system consisting of two simple harmonic oscillators coupled together. **Relevant reading includes sections 14.1-14.2 and 15.6 of Giancoli.** If you are feeling overwhelmed with this new material, the textbook is a GREAT place to start looking for help!

#### 2 Procedure

#### 1. Spring Calibration:

Measure the spring constant of springs labeled spring #1 and spring #2. To do this, first suspend one of the springs vertically and note its equilibrium position. Next, suspend a series of about six different masses (e.g. 50-100 grams, step by 10 grams) from the spring. For each mass, measure the increase in the length of the spring beyond its rest length and record it in the table below. (Repeat this process for the other spring).

When the mass is hanging from the spring and is motionless (thus definitely not accelerating), the net force on the mass must be zero by Newton's 2nd law

$$F_{net} = \sum F = F_{spring} + F_{gravity} = -k(x - x_{eq}) + (-mg) = 0.$$
(4)

In other words, the upward (positive) force from the spring must just balance the downward (negative) gravitational force. If we chose  $x_{eq} = 0$ , we can rearrange our second law expression to get:

$$kx = -mg. \tag{5}$$

Note that we have a linear relationship between the displacement x and the mass m. Also, note that our displacement due to the hanging mass is down which is negative as defined

here. This data can be plotted and the spring constant determined from the slope of a straight-line fit (see Question 1). It is likely useful to recall that  $g = 9.80 \text{ m/s}^2$  is the acceleration due to gravity near the surface of the Earth.

	Spring 1		Spring 2
Mass (g)	Displacement (cm)	Mass (g)	Displacement (cm)

#### 2. Simple Harmonic Oscillator:



Figure 2: A simple harmonic oscillator using one mass and two springs.

Set up the system shown in Fig. 2 above using springs #1 and #2. Connect spring 1 to one end of the air track and the glider. Connect spring #2 to the other end of the glider and to a bar mounted roughly 2/3 of the way down the air track. Allow the system to come to rest, and note the equilibrium position of the glider on the centimeter scale on the air-track (you may use the left or right edge of the glider as a reference position). Displace the glider a few centimeters from its rest position and observe the resulting oscillations (i.e. play a little bit!).

Find the Mass Dependence of a Simple Harmonic Oscillator: First, find the mass of the air-track glider using a balance. Then measure the oscillation period as a function of glider mass. The period of oscillation is the time required for the glider to execute a complete back-and-forth motion; it is convenient to measure 10 periods and then divide the result by 10 to get the time for one period. You want to measure the period for several different glider masses so you will need to vary the glider mass by adding masses symmetrically (equal mass added to left and right sides of the glider). Use five different masses, with a maximum of 200 grams. Check first that with 200 g the glider does not experience significant friction with the air-track – if it does see the lab instructor.

Record your results in the table below:

		semator
Mass (g)	Period (sec)	$\omega~{ m (rad/s)}$

#### Simple Harmonic Oscillator

#### 3. Coupled Harmonic Oscillators:

Set up the system shown in Fig. 3. Find the mass of both gliders using a balance and record the results. Be sure that the outer springs are labeled spring #1 and spring #3 (they are treated as having the same spring constant  $k_1$ ) and the inner spring is labeled spring #2. Now hold the left glider still while displacing the right glider from equilibrium, and release from rest. The oscillatory motion of the gliders about their equilibrium positions is rather complicated!



Figure 3: Coupled harmonic oscillators.

Despite the apparent complexity of an arbitrary oscillation, this system has two very simple modes of oscillation in which all the parts move at the same frequency. To see one such mode, pull each glider the same distance to the right of equilibrium, and release from rest. The masses move together in simple harmonic oscillation. This mode is called the *symmetric mode* of oscillation. Measure and record the period of the symmetric mode of oscillation.

Now we will examine the other simple mode of oscillation. Pull the masses apart, pulling each mass an equal distance away from equilibrium, and release from rest. Note that the masses move toward each other, then away from each other, in alternating cycles. Each mass alone is undergoing simple harmonic oscillation about its equilibrium point. This mode is called the *anti-symmetric mode* of oscillation. Measure and record the period of the anti-symmetric mode oscillation.

It turns out that any other oscillation that you might observe with this system is "sim-

ply" a weighted combination (or **superposition**) of these two modes of oscillation going on at the same time.

### 3 Questions

- 1. Recall the relation kx = -mg discussed in Procedure 1. Make appropriate plots to find the spring constants of **springs #1** and **#2** using your data from Procedure 1. Decide which quantities should be plotted on which axes and deduce the spring constant k from the slope of your plot. Be sure to calculate the uncertainty of k. Explain your reasoning briefly, and report your values for k in the form value  $\pm$  uncertainty with appropriate significant digits and units.
- 2. (a) Write down Newton's second law ( $\sum F = ma$ ) to describe the horizontal forces on the glider in Procedure 2 in which you to observe the mass dependence of the SHO. Your equation should contain only the variables  $k_1$  and  $k_2$  (spring constants), x (displacement of the glider from equilibrium), m (mass of the glider), and a (acceleration of the glider). You should have two different horizontal force terms, one for each spring.
  - (b) Compare the equation of motion you wrote in part (a) with the equation of motion for a SHO (Eq. 1). Knowing that the angular frequency  $\omega$  of the oscillator in Eq. (1) is  $\omega = \sqrt{\frac{k}{m}}$ , what is the predicted angular frequency of the glider in Procedure 2? Express your answer in terms of the given symbols. (Hint: The equations are very similar-you can find a letter-by-letter analogy. Which combination of constants in the equation of motion you wrote in part (a) functions like the k in Eq. (2)?)
  - (c) Plot  $\omega^2$  vs.  $\frac{1}{m}$ , using the data taken in Procedure 2. Note that angular frequency ( $\omega$ ) is related to the measured period (T) by  $\omega = 2\pi/T$ .
  - (d) Considering your answer to part (b), what should the slope of the plot be, in terms of  $k_1$  and  $k_2$ ? First find an algebraic expression and then a value, using the values for  $k_1$  and  $k_2$  determined in Question 1. What is the uncertainty in this prediction (based on the uncertainties of  $k_1$  and  $k_2$ )? Report your answer in the form: value  $\pm$  uncertainty, with an appropriate number of significant digits and proper units.
  - (e) Compare the measured slope from part (c) to the predicted slope from part (d). Include your uncertainties! Do your values agree with each other? Explain.
- 3. In this question, we will compare the oscillation periods of the coupled SHO system to the periods predicted from Newton's laws.
  - (a) **Symmetric mode:** Since the middle spring remains unstretched, we can treat it as a rigid, massless rod joining the two gliders. Effectively, we have a single rigid object of mass equal to twice the mass of a single glider cart connected to two equal springs of spring constant  $k_1$ . The oscillation frequency should thus be  $\omega = \sqrt{\frac{2k_1}{2m}} = \sqrt{\frac{k_1}{m}}$ . Find the percent difference between this prediction and the observed angular frequency. (Assume both gliders have the same mass, equal to the average of the two measured masses).

(b) Anti-symmetric mode: Once again, we focus our attention on the middle spring. The middle spring is alternately stretched and compressed symmetrically about its center point in this mode. In fact, the center point of the middle spring never moves! So we can imagine attaching this point to a fixed support, thus separating the system into two completely separate, non-interacting systems on the left and right. The spring constant of a half-spring is  $2k_2$ , so the angular frequency is  $\omega = \sqrt{\frac{k_1+2k_2}{m}}$ , by an argument identical to the one used in Question 2(b). Find the percent difference between this prediction and the observed angular frequency for the anti-symmetric mode.

### PHYSICS 120 - EXPERIMENT 6 Standing Waves on a String

#### 1 Introduction

A standing wave is the simple harmonic motion of a continuous system, with the various parts of the system moving together at the same frequency and phase. Examples of standing waves in familiar systems range from sound waves in trumpets and organ pipes or oscillations of a guitar string to the electron probability distribution in an atom. In this experiment, we will explore some properties of standing waves exhibited by a string with fixed ends in transverse oscillation.

Consider a thin string of uniform **mass density**  $\mu$  held under **tension force**  $F_T$  (see Fig. 1). One end of the string is attached to a mechanical driver, a device that vibrates and thereby shakes the string up and down, creating waves. The other end of the string passes over a pulley and is attached to a mass m, so that the tension in the string is given by  $F_T = mg$ , where g is the acceleration due to gravity.



Figure 1: Standing waves on a string. (a) Equilibrium configuration. (b) Second harmonic (n = 2) mode of oscillation.

The motion of this mechanical system can be derived using the usual laws of mechanics, applying F = ma to each small segment of string, and in fact the problem has a straightforward analytic solution. It turns out that if the driver's motion is simple harmonic, each point on the string also oscillates in simple harmonic motion about its equilibrium position, and all points on the string moves together at the same frequency and phase. Furthermore, the standing wave is sinusoidal, meaning that if you take a high speed photograph of the string at any instant, the string would look like a sine function. The displacement (D(x, t)) of the string at any point x on the string at

time t is given by

$$D(x,t) = D_0 \sin\left(\frac{n\pi x}{L}\right) \cos(\omega t) \tag{1}$$

where L is the length of the string,  $\omega$  is the angular frequency of the driver, the constant  $D_0$  is the amplitude of the motion (measured in meters), and n is a positive integer called the mode number and corresponds to the nth harmonic.

We will not concern ourselves with the derivation of Eq. (1), but we will instead investigate some properties of the standing waves. Note that D(x, t) is automatically zero at all times at x = 0 and L = 0, the two ends of the string. (It may seem surprising that the string's displacement is zero at the driver-this is really only approximately true. For small driver amplitudes, we can make the string's displacement nearly zero at the driver.)

Points where the string's displacement is always zero are called nodes. When the mode number n = 1 (i.e. the first harmonic or the fundamental frequency), there are no other zeros of the displacement (D(x,t)). When n = 2, there is a node (zero) at the midpoint of the string  $(x = \frac{L}{2})$ . When n = 3, there are nodes at  $x = \frac{L}{3}$  and  $x = \frac{2L}{3}$ . We can understand the nodes in a simple way: an integer number of humps of the sine function must fit on the string between its ends.

From the above reasoning, we know that the possible wavelengths of the standing waves on the string are given by

$$\lambda_n = \frac{2L}{n} \tag{2}$$

where  $\lambda_n$  is the wavelength of the standing wave when the string is oscillating in the *n*th harmonic. We also make use of the general wave relation

$$v = \lambda f \tag{3}$$

where v is the velocity of waves on the string,  $\lambda$  is wavelength, and f is the frequency of the driver producing the waves. Finally, to apply the general wave relation (3) to the specific problem of waves on a string, we will use the fact that the velocity of waves on a string is given by

$$v = \left(\frac{F_T}{\mu}\right)^{1/2} \tag{4}$$

where  $F_T = mg$  is the tension on the string and  $\mu$  is the mass density of the string.

We will investigate the standing waves on a string depend on the force of tension  $F_T$  in the string and the length L of the string. In the process, we will see that the driven string can oscillate in standing wave modes with wavelengths given by Eq. (2).

### 2 Procedure

1. Position the driver approximately 1.0 m from the pulley, and fix its position using a C-clamp. Record the length of the string between driver and pulley. Turn on the driver (by plugging it in). Now suspend some mass from the end of the string hanging over the pulley. You will find that if just the right amount of mass is suspended from the string, the string begins to oscillate with a large amplitude - at this point you have found a harmonic, or standing wave! Your goal is to observe all the modes from second harmonic (n = 2) through the ninth harmonic (n = 9) or higher. Record the mass m and the harmonic number n.

**Two hints:** The mass hanger is convenient to use when suspending large masses, but is actually too heavy for several of the harmonics. The approximate condition for a harmonic can be found by manually increasing or decreasing the tension (gently pulling down or lifting up) on the string-this may help you locate a harmonic when you are near one.

nth harmonic	Mass (g)	$\#  ext{ of nodes}$	# of antinodes	Overtone
2				
3				
4				
5				
6				
7				
8				
9				

 $L = \_\_\_$  cm

2. Fix the mass on the string to obtain the 5th harmonic (6 nodes, 4 nodes between the endpoints). Record the string length (driver to pulley). Then vary the length L of the string by gradually moving the driver closer to the pulley. Record the string length L and the harmonic number n whenever you see the string vibrate in a standing wave, for n = 2, 3, 4, and 5.

Mass =\_\_\_\_\_g

nth harmonic	Length (cm)
2	
3	
4	
5	

3. Measure a length of similar string. Measure its mass.

### 3 Questions

- 1. Using Eqs. (2), (3), and (4), derive a relation between the harmonic number n and the mass m suspended from the string, in terms of the constants L (string length), g (acceleration due to gravity),  $\mu$  (mass density of the string), and f (frequency of the driver). Use symbols (letters), not numbers. Show and explain all the steps in your derivation.
- 2. With the relation you derived in Question 1 in mind, make a plot of your data from Procedure 1 from which you can determine the mass density  $\mu_1$  of the string. The driver frequency f is 120 Hz. Explain clearly how you obtained  $\mu_1$  from the plot. Be sure to determine the uncertainty in  $\mu_1$  after finding the uncertainty in your slope and state your result and its uncertainty in the form  $\mu_1 \pm \delta \mu_1$  with proper units and significant digits.
- 3. Make an appropriate plot of the data from Procedure 2. Using the relation derived in Question 1, determine  $\mu_2$  from your plot. Explain clearly how you obtained  $\mu_2$  from the plot. Be sure to determine the uncertainty in  $\mu_2$  after finding the uncertainty in your slope and state your result and its uncertainty in the form  $\mu_2 \pm \delta \mu_2$  with proper units and significant digits.
- 4. Calculate  $\mu_3$  from Procedure 3. Be sure to determine the uncertainty in  $\mu_3$  after finding the uncertainty in your slope and state your result and its uncertainty in the form  $\mu_3 \pm \delta \mu_3$  with proper units and significant digits.
- 5. Are your results for  $\mu_1 \mu_2$ , and  $\mu_3$  in agreement given your calculated uncertainties? Explain. Are there overlap in any of the results? Are there any intervals in which all the results overlap?
- 6. (a) Calculate the speed of waves on the "A string" of a guitar when it oscillates in the fundamental mode (or 1st harmonic). The length of the string is 63.5 cm and the frequency is 110 Hz.
  (Extra information for those interested in the physics of music: The guitar A string is two octaves below A440 Hz, the A above middle C. One can find the approximate frequency of any note knowing that the A above middle C has a frequency of 440 Hz, and the frequencies of the notes on the tempered scale are arranged approximately in geometric series with each half-tone <sup>12</sup>√2 times higher in frequency than the previous. If you proceed 12 steps up the chromatic scale you will find you have doubled the starting frequency or gone an octave from your starting note.)
  - (b) I weighed a 3.3 cm snippet of the A string on a good analytical balance and found the mass to be 0.2039 grams. What is the mass density of the A string?
  - (c) Under what tension (in Newtons) must the string be if it is to have a fundamental frequency of 110 Hz?
- 7. Sketch the 4th harmonic. Identify the nodes, anti-nodes and wavelength in your sketch.

### PHYSICS 120 - EXPERIMENT 7 GEOMETRIC OPTICS

### 1 Introduction

Many properties of light can be understood by thinking of light as a plane wave propagating in a straight line, called a ray. Surprisingly, the wave nature of light is not relevant for understanding many important optical devices, whose behavior can be understood in terms of the geometrical properties of the straight-line light rays. A basic understanding of geometric optics is important for workers in any technical field, since many laboratory instruments, such as telescopes, microscopes, and camera lens systems, are optical or have optical components. We will investigate some properties of thin lenses and verify some of the basic equations describing their behavior.

Arguably, the most important optical device is the thin lens. In today's lab, we will investigate two classes of thin lenses: **converging** and **diverging**.

A converging lens is a piece of glass with curved surfaces, thicker in the middle than at its edges. Often, because of ease of manufacture, the curved surfaces are sections of spheres. Using simple geometry and Snell's Law of refraction:  $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ , it can be shown that parallel rays of light incident from the left along the axis of the lens are focused through a common point to the right of the lens (see Fig. 1).



Figure 1: Ray Diagram illustrating the focal point of a converging lens.

This point, called the focal point (F), is located along the principle axis of the lens a distance f (the focal length) from the center of the lens. If a screen is placed one focal length (f) from the lens, a bright point-like image will be visible on the screen. It turns out that the single length-scale f completely describes the behavior of the lens. Suppose a light source (i.e. the object) is placed a distance  $d_o$  to the left of a lens of focal length f. Then an image of the source/object will be focused on a screen placed a distance  $d_i$  to the right of the lens. This image, formed by focused light rays, is called a **real image**. The image distance  $d_i$  can be predicted by using the **Lens Equation**:

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

Using some geometry, it can also be shown that the image is magnified (or reduced) in size compared to the size of the source. If  $h_o$  is the diameter (or height) of the source, then the diameter (or height) of the image  $(h_i)$  is given by the **Magnification Equation** to be

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$
(2)

The quantity m, called the **magnification**, is equal to the ratio of **image diameter** (or image height) to **object diameter** (or object height) or, alternatively, it can be expressed negative the ratio of the image distance to the object distance.

We will make measurements to test the Lens Equation and the Magnification Equation for a spherical converging lens.



Figure 2: Source distance  $d_o$ , image distance  $d_i$ , source height  $h_o$ , and image height  $h_i$  for a converging lens.

Note: While the geometrical ray picture can account for the image-forming properties of lens systems, the ray picture cannot explain other interesting optical phenomena, such as interference and diffraction of light. An explanation of these phenomena requires explicit consideration of the wave properties of light. We will investigate some of these properties in next week's lab.

A diverging lens is a curved piece of glass (often with spherical surfaces) which is thinner in the middle than at the edges (i.e. a concave lens). If parallel rays of light are incident from the left on a diverging lens, the rays diverge apart on the right side of the lens as shown in Fig. 3. To an observer to the right of the lens, it appears as if the light is all coming from a single point source a distance f to the left of the lens. This image of a bright point-like object to the left of the lens is called a **virtual image**, since the light rays do not actually pass through this point and so an image can not appear on a screen.



Figure 3: Ray Diagram illustrating the focal point of a diverging lens.

It turns out that the Lens Equation and Magnification Equations both hold for diverging lenses as well as converging lens **if certain sign conventions are used**.

- The focal length for a converging lens is positive (f > 0)
- A diverging lens has a negative focal length (f < 0)
- The image distance  $d_i$  is positive  $(d_i > 0)$  if the image is on the opposite side of the lens as the source
- Otherwise,  $d_i < 0$  (image on the same side of lens as the source)
- The source distance is always positive  $(d_o > 0)$  for a single lens system

### 2 Procedure

- 1. Find and record the focal length f of your converging lens by imaging light from objects outside the window (i.e. a light source from very far away) onto a screen. Rays of light from beyond the window are nearly parallel and a focused image will be formed when the screen is positioned a distance f from the lens. To gain a sense of the uncertainty in f, examine the range over which you can move the lens and still conclude that your image is "focused." Record these results. See Question 3a.
- 2. Next, a series of measurements will be made to check the Lens Equation and the Magnification Equation. On your light source you will observe a disk with several aperture shapes. Choose the L shape. Measure and record the height of the source aperture L. Position the light source at one end of the track and position the screen 1.00 m from the source. Place your converging lens between source and screen and, while keeping the source-screen distance constant, find and record the **two** positions of the lens where a focused image is formed on the screen. Also, measure and record the heights of both focused images and note the orientations of the images (upright or inverted).

Now move the screen 5.0 cm closer to the source and repeat the measurements. Continue

the process until a source-screen distance is reached at which only a *single* position of the lens gives a focused image on the screen. Find this special source-screen distance as exactly as possible and record it. What happens when the screen is moved even closer to the source? Move the screen 5.0 cm closer to the source, and try to position the lens to form a focused image of the source on the screen. See Questions 1, 2, 3b, and 4.

Screen Source Distance $(D)$	$d_o(\mathbf{A})$	$d_i$ (A)	$h_i$ (A)	$d_o$ (B)	$d_i$ (B)	$h_i$ (B)
100 cm						
$95~\mathrm{cm}$						

3. In this procedure, you will measure the focal length of your diverging lens. For this experiment, you will need the result that two thin lenses with focal lengths  $f_1$  and  $f_2$  placed in "close contact" function identically to a single thin lens with effective focal length f given by

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \tag{3}$$

Place the source at one end of the track. Place your converging and diverging lenses as close together as their respective mounts will allow. Experiment with different source, lens, and screen positions until you find one where a real image of the source appears focused on the screen. Record  $d_i$  and  $d_o$ . (See Question 5)

4. In this procedure you will investigate the effects of an aperture placed between a lens and a focused image. Insert the mount containing a disk with 6 apertures (5 circular holes of decreasing size and a semi-circular hole) just in front of the lens (on the source side of the lens, as near the lens as possible). Observe closely the effect of each aperture on the image and record your observations. See Question 7.

### 3 Questions

- (a) As you have seen in Procedure 2, for a given source-screen separation D there are two different positions of a converging lens that result in a focused image on the screen. For real images, it must be that D = d<sub>i</sub> + d<sub>o</sub> (see Fig. 2.). For a fixed D and f, show that the Lens Equation predicts two locations at which an image can form on the screen. Use symbols (letters), not numbers. (**Hint:** Put D = d<sub>i</sub> + d<sub>o</sub> into the Lens Equation, and solve the resulting quadratic equation for d<sub>i</sub>, showing that there are two solutions for d<sub>i</sub>.) What condition must be satisfied in order to actually have two image locations (i.e. when is √(b<sup>2</sup> 4ac)) real)?
  - (b) Looking at the same solution found above, under what conditions will you have a single image (i.e. a single solution to the quadratic equation)? Express your answer in terms of the source-screen separation  $D = D_1$  and the focal length f.
  - (c) What happens when the source-screen separation D is less than  $D_1$ ?
- 2. (a) Plot experimentally-determined  $d_{i,1}$  vs. theoretical  $d_{i,1}$  and experimentally-determined  $d_{i,2}$  vs. theoretical  $d_{i,2}$  (two different plots). The experimentally-determined values of  $d_{i,1}$  and  $d_{i,2}$  were measured in Procedure 2. The theoretical values of  $d_{i,1}$  and  $d_{i,2}$  are determined by your analysis for Question 1, in which you should take the measured focal length f from Procedure 1 and the measured source-screen distance D in Procedure 2 to be exact quantities.
  - (b) Explain how your two plots do or do not support the validity of the Lens Equation. In other words, if the Lens Equation were valid, what would you expect your plot to look like? Be as precise and complete as possible (specify its predicted shape, slope, y-intercept, anything else that may be useful).
- 3. (a) What is the focal length you determined in Procedure 1? Report your finding for the focal length in the form  $f \pm \delta f$  with proper units and significant digits.
  - (b) Make a plot of D vs.  $d_i d_o$  and use your plot to determine the focal length of your lens. Report your finding for the focal length in the form  $f \pm \delta f$  with proper units and significant digits. Explain clearly and justify how you determined the focal length from your plot.
  - (c) Do the results you found for the focal length in Procedures 1 and 2 agree? Explain.
- (a) Plot the measured magnification (m = h<sub>i</sub>/h<sub>o</sub>) vs. the theoretically-predicted magnification (m = -d<sub>i</sub>/d<sub>o</sub>) for the data taken in Procedure 2. Of the images formed for fixed source-screen separation D, plot only the distance for the image formed when the lens was nearer the source (i.e. the bigger image).
  - (b) Explain how your plot does or does not support the validity of the Magnification Equation. Be as precise and complete as possible (i.e. mention the shape, slope, and *y*intercept of the plot).
- 5. Use the Lens Equation, Eq. 3, and the known value of f for the converging lens to find the focal length of the diverging lens. Show your calculation fully. Report your finding for the focal length in the form  $f \pm \delta f$  with proper units and significant digits.

- 6. (a) When finding the focal length of a converging lens in Procedure 1, you imaged the view from the window onto a screen. Suppose that a tree 30.0 m from a lens of focal length 10.0 cm is imaged to a 12.0 cm high focused image of the tree on a screen. How tall is the tree?
  - (b) Suppose the focused image of a car passing by on South Street (100 m from your lens) crosses your 8.0 cm-wide screen in 2.0 sec. Your lens has focal length 20 cm. Making any reasonable assumptions necessary (and explaining them!), find the speed of the car in m/sec. If the car is driving eastward, in what direction does the image move?
- 7. Report your observations made in Procedure 4. Were the results surprising? Explain your observations in the context of the ray model.

### PHYSICS 120 - EXPERIMENT 8 Interference and Diffraction of Light

### 1 Introduction

Until now, we have exclusively considered the Ray Model to describe light. The field of geometric optics is based upon this model and by using it we can describe a great number of phenomena related to reflection and refraction. However, in an experiment performed in 1801 by Thomas Young, some of the first convincing evidence for the wave nature of light was discovered. In his experiment, he saw behavior of light that could not be explained by the ray model. In fact, this behavior of light was recognized as a clear indication of the wave phenomena of interference and diffraction that we have already observed in the context of water waves and sound.

We rarely notice wave effects related to light in our everyday experience, and this is easily explained by considering that the dimensions of ordinary objects are much larger than the wavelength of light and that ordinary light is neither monochromatic nor coherent. It may not be totally clear why these facts mean together explain why we do not experience the wave-nature of light in our every day life - but hopefully through doing this experiment you will better understand why this is the case.

In this experiment will be using a laser as a source of **coherent**, **monochromatic** light and considering the interaction of laser light with an object with dimensions on the order of the optical wavelength. Because of this we will see clear manifestation of the wave phenomena of interference and diffraction.

In the first experiment, we consider the interference pattern produced when light is incident on a pair of narrow slits some distance apart. This famous two-slit experiment (known as the Young double-slit) is shown schematically in Fig. 1. (See Giancoli 35-3 3rd ed. or 34-3 4th ed. for details)

Laser light of wavelength  $\lambda$  shines on two narrow slits in an opaque screen that are separated by a distance *a*. The slits now can be viewed as **two** sources of coherent, monochromatic light. **Coherent** means that there is a definite phase relation between the light intensity (a sine wave) produced by each slit – the waves are in phase. **Monochromatic** means that all the waves from the source have a single wavelength (or single color).

Consider the light intensity reaching a point P on a screen a distance L from the two slits, and let  $r_1$  be the distance from slit #1 to P and let  $r_2$  be the distance from slit #2 to P. If the source waves from slit #1 and slit #2 are in phase and the difference in path lengths is an integer number of wavelengths (i.e.  $r_1 - r_2 = n\lambda$ ) the light waves from slit #1 and slit #2 interfere constructively, so point P is bright. On the other hand, if the difference in path lengths is equal to an integer plus a half number of wavelengths (i.e.  $r_1 - r_2 = (n + \frac{1}{2})\lambda$ ), then the light waves from slit #1 and slit #2 interfere destructively. In this case, there is complete



Figure 1: Illustration of the Young Double-Slit Experiment

destructive interference and the point P is dark.

Thinking along these lines, an interference pattern appears on the screen consisting of a series of bright and dark fringes (with the bright fringes corresponding to constructive interference of the light and the dark fringes corresponding to destructive interference). This pattern appearing is an indication of the wave-like nature of light. Using some geometry, one can show that the *condition for destructive interference* is given by:

$$a\sin\theta = (n + \frac{1}{2})\lambda.$$
(1)

When the angle  $\theta$  is small ( $\theta \ll 1$  radian),

$$\sin\theta \approx \tan\theta = \frac{x_n}{L} \tag{2}$$

where  $x_n$  is the distance on the screen between the central (n = 0) maximum and the *n*th bright fringe.

- We will perform the two-slit experiment to observe the fact that, indeed, light does have wavelike properties.
- We will test Eq. (1), and in the process determine the wavelength  $(\lambda)$  of light from a Helium-Neon laser.

**Diffraction** is a wave phenomenon in which a wave, incident on a barrier, spreads out into the region behind the barrier (See Giancoli 36-1 3rd ed. or 35-1 4th ed. for details). The diffraction of sound waves around corners is an example of wave diffraction. With light, diffraction manifests itself as the spreading of light into the geometric *shadow region* behind an opaque object. One may observe diffraction when coherent light is incident on a single narrow slit of width comparable to

the optical wavelength. For single-slit diffraction, the light intensity pattern visible on a far-away screen looks like a series of bright and dark fringes, much like the interference pattern from the double-slit (see Fig. 2).



Figure 2: Illustration of diffraction from a single slit.

In fact, one may think of the single slit as a row of a large number of point sources of light, and the fringes are due to interference of light waves produced by these light sources. This reasoning can be made quantitative, and the spacing  $\Delta x$  between the successive minima is given by

$$b\Delta x = \lambda L \tag{3}$$

where b is the width of the single slit. Actually, the above equation holds for all fringes in the diffraction pattern except for the central bright fringe, which has width  $2\Delta x$  between the dark fringes on either side. We will perform the single slit diffraction experiment to test Eq. (3), providing another means of measuring the wavelength ( $\lambda$ ) of our laser source.

### 2 Procedure

1. Turn on the laser.

Caution: Do not look directly into the laser beam or point it toward anyone else – direct viewing of the very intense beam of light can damage your eyes!

2. Mount the slit-film in front of the laser. The laser-slit distance should be about 1 m (less is ok); the laser-screen distance should be at least 2 m (more is better). The laser should be pointed with its beam nearly perpendicular to the wall. Tape a piece of white paper to the wall to serve as your observation screen. Carefully measure the distance L from the slit-film to the observation screen.

- 3. Double-Slit Experiment: Adjust the slit-film position so that the beam is centered on the narrowest of the 4 sets of double slits. Then adjust the slit-film so that the beam reflected back from the glass (called the *retroreflected beam*) goes back to the laser, insofar as possible. This procedure ensures that the beam is normally (perpendicularly) incident on the slit-film. Re-check that the beam is centered on the slits. Then measure and record the distance between successive fringes in the interference pattern. Include in your report an image of each interference pattern with a ruler next to it. Hint: Your results will be more accurate if you measure the length of n successive fringes, and then divide by n
- 4. Repeat the procedure for the other double-slits. The slit spacing is given in the table below.

	I Data
Double Slits	Single Slits
Spacing $a$ (cm)	Width $b$ (cm)
0.01756	0.01178
0.03388	0.02044
0.0690	0.03499
0.1380	0.07428
	0.1441

Slit-film Data

- 5. Diffraction Experiment: Now adjust the slit-film to observe the single-slit diffraction patterns. Measure the spacing between successive dark fringes as before. Again, it is best to measure the length of n fringes and divide by n. Be careful to count the central bright fringe as a double fringe, since the distance between the dark fringes on either side of it is  $2\Delta x$ . Repeat for all 5 of the single slits.
- 6. Diffraction Grating Experiment: (*Optional* laser fun!) If time remains, try putting the beam through some of the other patterns on the slit-film. The diffraction gratings (*n*-slit interference patterns) are particularly interesting. Also, take another look at the widest of the 2-slit interference patterns. It looks like some of the bright fringes are missing. Why is this? (Hint: Consider both diffraction from each individual slit and interference between slits.)
- 7. Turn the laser off.

### 3 Questions

- 1. Using Equations 1 and 2, derive an expression for  $\Delta x$ , the distance between two successive bright fringes (e.g. the *n*th and (n + 1)th bright fringes) in the two-slit interference pattern. Express  $\Delta x$  in terms of the slit spacing (a), the slits-to-viewing screen distance (L), and the wavelength ( $\lambda$ ). Use letters, not numbers. Show that  $\Delta x$  does not depend on *n*.
- 2. (a) Using the double-slit data and the relation you derived in Question 1, make a plot to determine the wavelength (λ) of the He-Ne laser. Explain clearly how you determined λ from your plot. Be sure to determine and state the uncertainty in your value of λ. Report your finding for the wavelength in the form value ± uncertainty with proper units and significant digits.
  - (b) The actual wavelength of a He-Ne laser is  $0.6328 \times 10^{-4}$  cm. Does your experimental value agree with the stated value? Explain.
- 3. (a) Using the single slit data and taking note of Eq. (3), make a plot from which you can find the wavelength (λ) of the He-Ne laser. Explain clearly how you determined λ from your plot. Be sure to determine and state the uncertainty in your value of λ. Report your finding for the wavelength in the form value ± uncertainty with proper units and significant digits.
  - (b) Does your experimental value agree with the stated value? Explain.
- 4. Without referring to any *equations*, explain why the fringe separation increases as the viewing screen is moved farther from the slits in the two-slit experiment. You *may* use *pictures* to help illustrate your explanation.