Lab manual for Physics II - 20484

Department of Physics & Astronomy
Texas Christian University, Fort Worth, TX

Spring 2013

Contents

List of Figures

Lab report

You must hand in a typed lab report for every lab you perform. The lab report must include the following:

1. Type your name, date, the day of the week you did the lab, and the name of the TA. (5 points)

2. Introduction (15 points): The introduction should include a general overview of the experiment, the goal of the experiment, what you expect to find and the theory behind the experiment. Summarize the whole point of doing the lab. Your introduction should be about one page long.

3. Results (20 points): Present the data in the form of a table or a graph. Usually you will give details of what you observed in the lab. If you deviated from the instructions in the manual, explain you method. Only important information pertinent to the lab should be presented. Show examples of any calculations carried out including estimates of the error. Remember to include units.

4. Discussion/Conclusion (40 points): Discuss in your own words and from your point of view your results. Example: Looking at your results, tables or graph, can you see any general trend? What is the behaviour of the graph/line? What was the aim of the experiment? Have we achieved anything? If not, how large is the error? Does your result make sense? Can you compare your result to those from the books? What does the book say? Be sure to answer any questions asked in the lab manual. Of course, any additional requests or instructions by the TA must be addressed in the report.

Lab 1

Electric Field Mapping

1.1 Introduction

For macroscopic objects with electrical charges distributed throughout the volume, the calculations of the electrostatic forces from the Coulomb's formula is difficult. Therefore, it is useful to describe the interaction forces as a product of the charge, q, and the electric field intensity, E.

$$F = qE. \tag{1.1}$$

As seen from the above equation, the knowledge of the electric field enables calculations of the electrostatic forces. An electric field can be found by analyzing the map of the electric field lines. The electric field lines, also called the lines of forces, originate on and are directed away from positive charges, and end on and are directed toward negative charges. The electric field lines enable one to find the direction of the vector $\vec{E}$; the vector $\vec{E}$ is always tangential to the lines of forces. But to fully characterize the electric field vector, we need also to give its magnitude. The magnitude, or strength of the electric field, can be measured from the density of lines at a given point. For example, for point charges, the electric field is given by the formula

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}, \tag{1.2}$$

which predicts that the field intensity increases with decreasing distance, r, from the charge, q. The density of field lines is largest when close to the point charges and quickly decreases with distance. The goal of this experiment is to find the electric field lines for two or three objects.

The electric field lines can be found by plotting the equipotential lines of the electric field. If the large number of points of the same potential needs is found, they may be connected together with a smooth line or surface, which is called an equipotential line or surface. The electric field lines must always be perpendicular to the equipotential lines or surfaces.

1.2 Procedure

The experiment will be performed using the electric field mapping board, high resistance paper, a conductive ink, a power supply (or a battery) and a voltmeter. The conductive ink is produced from copper or nickel flakes in a suspension. When the ink dries, the metal particles settle on the

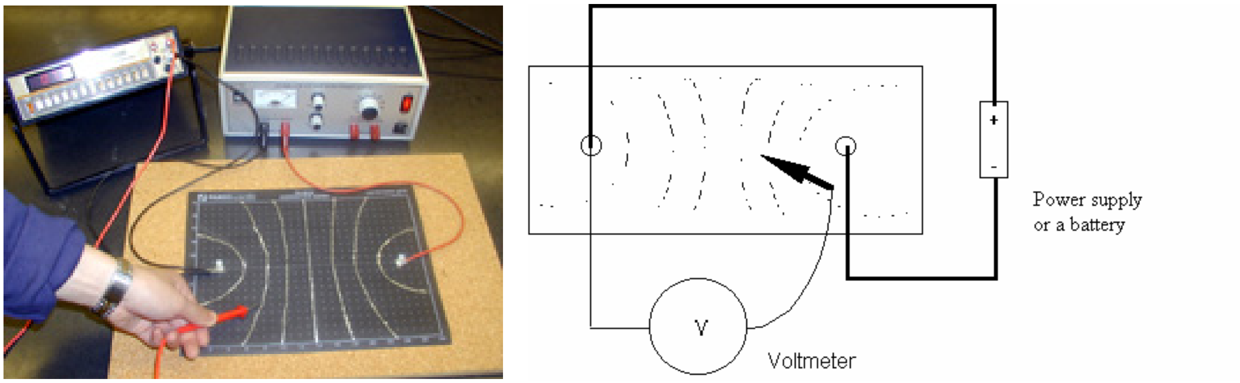

Figure 1.1: **Experimental setup.** A photograph (left) and schematic (right) of the experimental setup.

top of each other, forming a conductive path. The resistance of the ink is about 2 to 5 Ω/cm and can be neglected in comparison with the resistance of the paper, which is 20, 000 Ω/cm. Therefore, the potential drop across the electrodes can be considered negligible.

1. Place the conductive paper on a smooth surface (**do not place it on the corkboard**) and draw the electrodes with the conductive ink. Shake the conductive ink can vigorously for about one minute. Keep the can perpendicular to the paper while drawing the electrodes. When the line you made is spotty, shake the can again and draw over the line. A smooth solid line is essential for good measurements. Let the ink dry for about 20 minutes before making measurements. Therefore, plan your experiments and draw the electrodes as soon as possible.

2. Mount the conductive paper on the corkboard using push pins in the corners and connect the electrodes to a power supply (or a lantern battery) and to the voltmeter. Make sure that there is a good contact between the line, a wire, and the pin. If the electrode has been properly drawn, and a good electric contact has been established, the potential drop across the electrode should be less than 1%. If the voltage across the electrode is greater than 1%, then remove the pins from the corkboard and draw over the electrodes a second time with the conductive ink, or find another place to hook up the wire.

3. The equipotential surfaces are plotted by connecting one lead of the voltmeter to one of the electrode push-pins. This electrode becomes the reference. The other voltmeter lead (the probe) is used to measure the potential at any point on the paper simply by touching the probe to the paper at that point. Figure 1.1 (right) schematically indicates the method of mapping equipotentials. To map an equipotential, move the probe to the point at which the voltmeter is indicating the desired potential. Mark this point with a white pencil. Move the probe to a new position which maintains the voltmeter at the same reading. Mark this point. Continue in order to find a series of points at the same potential across the paper. Connect the points with a smooth line and write the potential difference. This is the equipotential line.

4. Repeat the measurements for different potentials between the probe and the reference electrode. Find at least 10 equipotential lines for voltages of 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22 V. From the symmetry, you can guess the 1, 3, 5 V surfaces and so you need not measure them. Do not try to mark the electric field lines; it takes too much time. Do it later at home. If the system has an axial symmetry, you may limit your measurement to one side of the symmetry axis. The equipotentials in the other half can be determined by reflecting the found lines about the axis.

1.2.1 Equipotentials between parallel lines

Find the equipotentials outside and inside the parallel lines which symbolizes a parallel plate capacitor. Next, sketch in lines of electric field force. Remember that lines of force are always perpendicular to equipotential surfaces; and, since conductors are equipotential surface, field lines must be perpendicular to the surface of both conductors. Sketch lines of forces first lightly, and when you have them right, draw them darkly. It is useful to choose a different color for the field lines than that used for the equipotential lines. Keep the same distance between the electric field lines close to the silver lines representing the capacitor. Remember that the electric field lines are perpendicular to the equipotential lines and to the metal surfaces.

In the report, answer the following questions:

1. What is the electric field inside the capacitor?

2. What is the electric field outside the capacitor? Is it constant?

3. How do the edges of the plates affect the electric field? (PHYS 20481 and PHYS 20484 only)

4. From the measurements, calculate the components of the electric field at the center of the capacitor and at a point at the edge. Since the potential has been measured in large steps of voltage, you can only estimate the components E_x and E_y from

$$(E_x, E_y) = -\left(\frac{\delta V}{\delta x}, \frac{\delta V}{\delta y}\right) = -\left(\frac{\Delta V}{\Delta x}, \frac{\Delta V}{\Delta y}\right). \tag{1.3}$$

1.2.2 Equipotentials between two parallel lines with a floating circular electrode

Draw a circular electrode between two parallel lines (Fig. 1.2) and map the equipotentials. The circular electrode symbolizes a hollow metal sphere between the capacitor plates. In the report, answer the following questions:

1. How does the circular electrode distort the field? Compare the result with those obtained for two parallel lines.

2. What is the electric field inside the circular electrode? What is the field on the electrode surface?

3. What is the potential of the circular electrode? What is the potential inside the electrode?

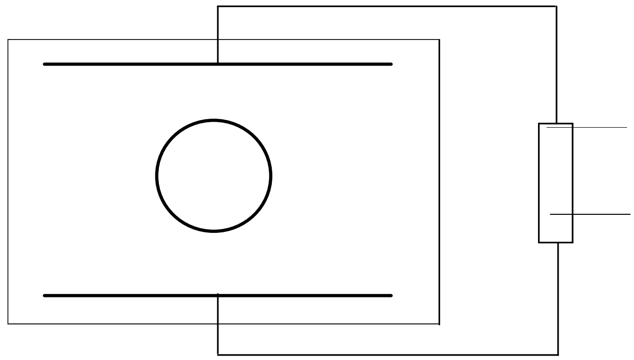

Figure 1.2: **Capacitor with a hollow metal sphere between the plates.**

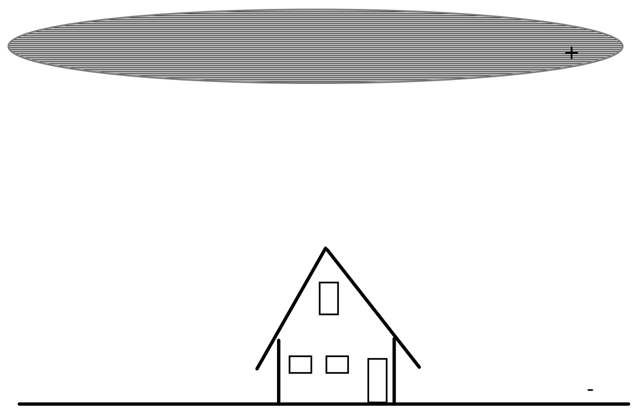

Figure 1.3: **Simulation of an electric field during a thunderstorm.**

1.2.3 Clouds and a house during a thunderstorm.

Draw two electrodes, one in the shape of a cloud, another in the shape of a house. Exaggerate the shape of the roof and make it very sharp (Fig. 1.3). During a thunderstorm, the clouds carry large charges which create an intense electric field between the clouds and the ground. Your electrodes simulate this charge separation and the generated electrostatic field. Map the equipotential lines and mark the electric field lines. In your report, discuss the distribution of the electric field lines, especially in the close proximity of the roof. Where will the lightning strike, outside the house or on the tip of the roof?

1.2.4 Quadruple moment

Draw the electrodes as in Fig. 1.4. Find the equipotentials and electric field lines. Determine the electric field components, E_x and E_y for two points on the xy plane.

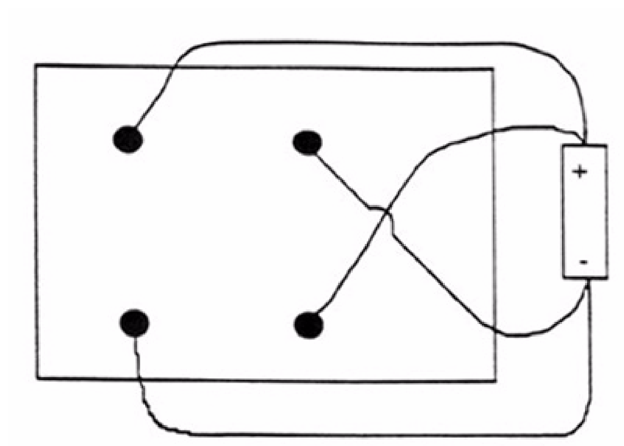

Figure 1.4: **Electric field mapping of a quadrupole.**

Lab 2

Electric measurements

2.1 Introduction

To find the resistance, one needs to measure the voltage across the resistor, V, and the current, I, flowing through the resistor. According to the Ohm's law the resistance, R, is given by the ratio:

$$R = \frac{V}{I}. \tag{2.1}$$

You will use a digital multimeter to find R, V and I. Our laboratory is equipped with first-rate instruments, which display 4 digits, see picture below. On the voltage scale you can measure 0.5×10^{-4} V to 1999 V; on the current scale you can measure 0.5×10^{-7} A to 10 A. Other multimeters used in this lab have different shapes but they all measure R, V, and I (Fig. 2.1).

As you look at the front panel of the multimeter, you notice that there are black and red jacks. Also on your workbench you may find red and black cables. It is a common practice to use a red wire for high voltage or positive signal and a black wire for low voltage or negative signal. We suggest that you should use this system in the laboratory since it is helpful in checking the wiring. (A different system is used in the wiring of buildings. White denotes the neutral wire; black is used to indicate wires under 120 V AC; red is reserved for 240 V. Green is always used for ground wires.)

Figure 2.1: **Multimeters** Typical analog (left) and digital multimeters (center and right).

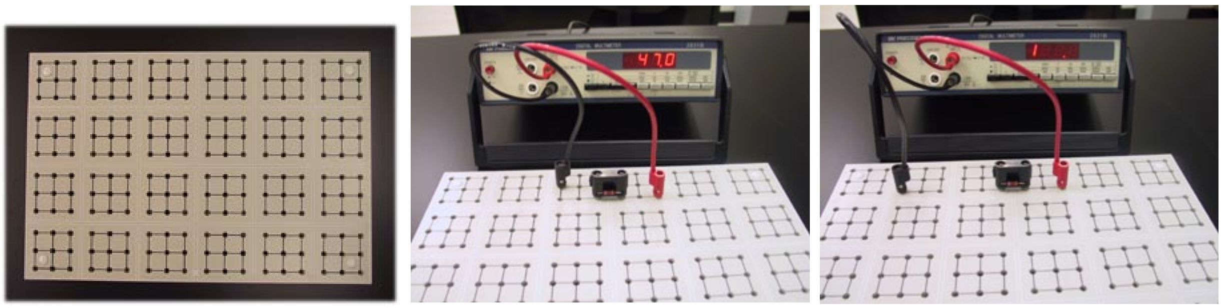

Figure 2.2: **The breadboard.** A breadboard (left) and examples of a good circuit (center) and a bad circuit (left).

2.2 Procedure

Set the meter to measure resistance (ohm, Ω) by depressing the HI Ωfunction switch. Connect a black lead to the common jack of the multimeter and a red lead to the A-Ωjack. Select a 1000 range. Please note that HI Ωrange is set to measure kiloohms, kΩ, combining it with the 1000 range this means that the maximum value to be measured is $1,000,000\ \Omega$ or 1 MΩ. Keep the leads apart and the display should flash. The flashing indicates that the measured resistance between two leads exceeds the maximum value of 1 MΩ. Next, grasp two exposed leads, holding one in your right hand and the other in the left hand. The meter will show the resistance of your body. Measure the resistance of your skin by touching two points on your skin about 2 inches apart. The resistance of the skin may vary greatly with the amount of moisture on the skin. If your skin is dry you may have to change the range from 1000 kΩ to 10 MΩ. If it is wet to display more significant digits, you may want to change the range to 100 kΩ.

2.2.1 Resistor color code

Determine the resistance of the 5 resistors provided. Each resistor to be measured must be connected between two posts on the "bread board". The breadboard shown in the photo allows you to built electrical circuits. The openings are designed to fit banana plugs and are arranged in the form of squares. There are nine openings per square. They are all connected internally, but separate squares are isolated. To built a circuit you need to plug in one end of the resistor into any opening in one square and another end into another square. An example is shown in Fig. 2.2. Here a resistor is mechanically attached to a banana plug, which is pushed into holes in adjacent squares. The leads are pushed into other holes in the same squares and a multimeter. You can read a measured value on the display. An example of a BAD connection is shown below. In this photo the black lead is attached to a square with no resistor attached and the display is blank. This circuit is open and the multimeter cannot measure anything.

For your convenience we attached the resistors to banana plugs. There are five different banana plugs with different resistors provided for each setup. The resistors are marked with four or five color bands. This is the resistor color code. The first two bands indicate two significant digits, the third indicates the power of ten, and the fourth band indicates the precision of the measurements. The fifth band (if present) indicates reliability. The color code key for resistors is given in Table

Table 2.1: Resistor color code.

First three bands	
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9
Tolerance band	
Silver	10%
Gold	5%
No band	15%

Table 2.2: Resistance measurements

No.	Measured resistance (Ω)	Color code value (Ω)	Difference (%)
1			
2			
3			
4			
5			

2.1. Always orient the resistors so that the gold or silver band, the so called tolerance or precision band, be on your right side. For example, a resistor with the following colors (from left to right), brown black red - gold tells us the first digit is 1 (brown), the second digit is 0 (black) and the power of ten is 2 (red). That gives us $R = 10 \times 10^2\ \Omega = 1000\ \Omega$. The gold band tells us that this is accurate to within 5%, so the actual resistance could range from $950\ \Omega$ to $1,050\ \Omega$.

Attach the meter leads to the breadboard and record the displayed values. DO NOT ATTACH ANYTHING TO THE 10 A PLUG OF THE MULTIMETER. Change the range so that the display will show all four digits. For resistance values less then $10\ \Omega$ depress the LO Ω and $10\ \Omega$ switches. Clip the test leads together. You may observe a non-zero reading (a few tenths of an ohm). The reading is due to the resistance of the test leads, fuses, and jacks. You may adjust the ZERO control (available only on analog meters) until the display shows 0.00, or subtract the value from any readings in this range, if such accuracy is required. Report the measured resistance values in Table 2.2 and compare the data with the values expected from the color code. Compare the difference with the estimated value from the fourth band of the color code.

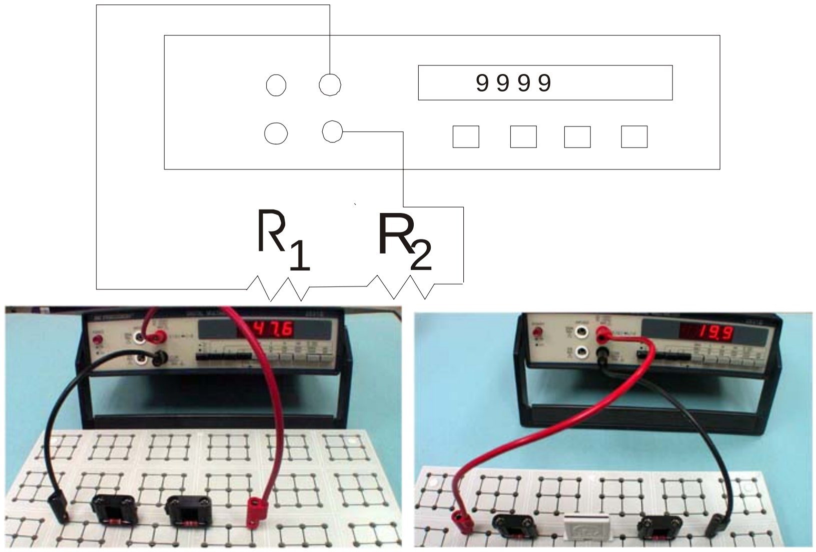

Figure 2.3: **Resistors in series.** The series circuit shown schematically at the top can be can wired in a number of different ways. The above photographs show two possible series combinations.

Table 2.3: Resistors in series measurements

R_1 (Ω)	R_2 (Ω)	Measured value (Ω)	Calculated value (Ω)	Difference (%)
1				
2				
3				

2.2.2 Resistors in series

Select two resistors of similar values. Measure each resistance. Then connect them in series on the bread board as shown in Fig. 2.3. In the left photo the resistors are plugged into adjacent squares, in the photo on the right the resistors are connected to distant squares and a white bridging plug is used to connect them. There are many other possible arrangements of resistors on the breadboard resulting in a series combination. Record the results. Compare the measured and expected values of two resistors connected in series. For the series combination, the theoretical value can be obtained from:

$$R_{\text{series}} = R_1 + R_2. \tag{2.2}$$

Report the experimental and theoretical values in Table 2.3.

2.2.3 Resistors in parallel

Connect the same two resistors in parallel as shown in Fig. 2.4. he photo shows one of many possible arrangements of the resistors on the breadboard that give the parallel combination. You may want to explore and build your own connections. Note, that you may work with a different multimeter!!!

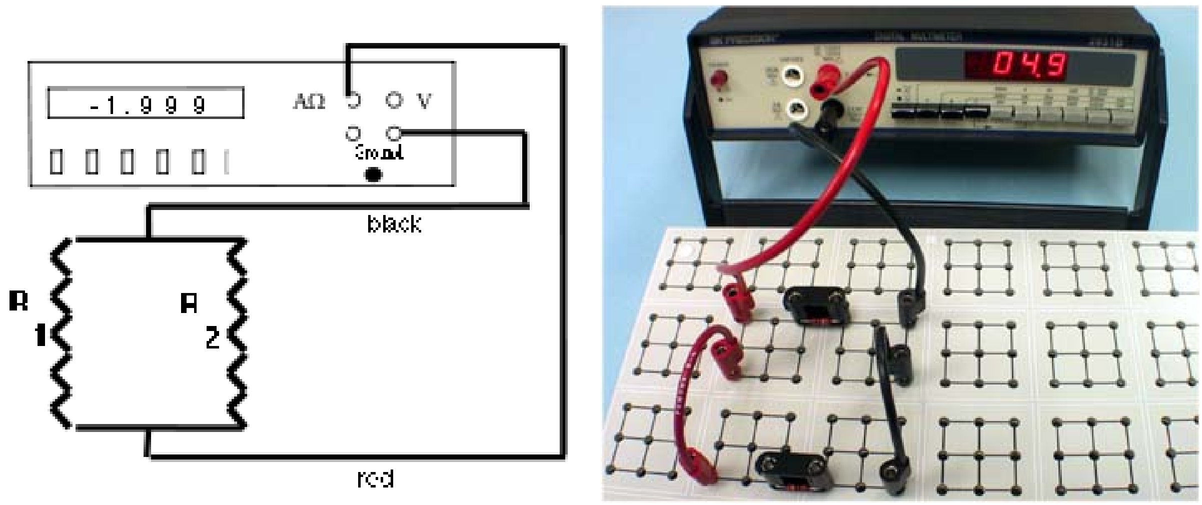

Figure 2.4: **Resistors in parallel.** The photo on the right shows one possible arrangement of resistors in parallel as shown schematically on the right.

Table 2.4: Resistors in parallel measurements

R_1 (Ω)	R_2 (Ω)	Measured value (Ω)	Calculated value (Ω)	Difference (%)
1				
2				
3				

Make your own arrangement of resistors in parallel. Compare the readings of the meter with the theoretical value:

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2}. \tag{2.3}$$

Compute the percentage difference and report the experimental and theoretical data in Table 2.4.

2.2.4 Ohm's law

Select a resistor of about 100 kΩ using the color code. IMPORTANT: Use the multimeter to read its actual value and record it in Table 2.5. Set up the circuit on the breadboard as shown in Fig. 2.5. The voltmeter is connected in parallel, the ammeter in series. The 5 volts can be obtained from a power supply you will find on the desk. Make sure that the positive terminal is connected to the red jack on the meter. Use one digital multimeter for "A", the ammeter, and another digital mulimeter for "V", the voltmeter, in the circuit.

The same instrument may be used as a voltmeter or an ammeter, and selecting proper functions is very important. Remember that the ammeter must be connected in series and the voltmeter always in parallel. Since you will use a DC current, select DCA and the range of about 100 µA for current measurements, and DCV and 10 V range for the voltage measurements. Record the

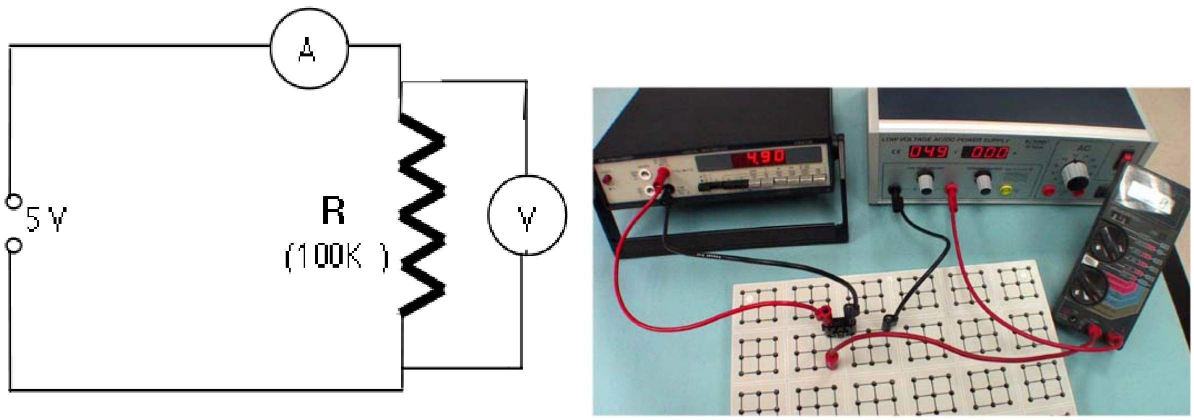

Figure 2.5: **Ohm's law circuit.** Ammeter is always in series, voltmeter is always in parallel. The photo shows the 100 kΩ resistor connected to a power supply (center) and an ammeter (right). The digital voltmeter (left) is connected in parallel to the resistor. Remember to depress the proper function and range switches.

current, I, and potential, V. Compute $V = IR$ to verify your voltage measurements. The two values agree if the voltmeter has an infinite internal resistance.

Replace the digital voltmeter with a standard voltmeter, as shown in the photo. Do not alter the power supply or the ammeter. The input resistance of the standard meter is smaller then that of the digital meter and may affect the measurements. You can read the value of the input resistance on the meters front panel. Adjust the meter scale appropriately and measure I and V. Compute $V = IR$.

The difference in the readings can be explained as follows. The resistance of the ammeter, R_A, is essentially zero. The resistance of the voltmeter, R_B, acts as a resistor in parallel with $R = 100$ kΩ. This means that the equivalent circuit can be drawn as shown in Fig. 2.6. The goal of this part of the experiment is to find the input resistance of the standard voltmeter.

The equivalent resistance can be found from the input voltage, which in this case is almost 5 V, and the current in the system.

$$R_{\text{equiv}} = \frac{V}{I}. \tag{2.4}$$

On the other hand the equivalent resistance can be written as (Eq. (2.3))

$$\frac{1}{R_{\text{equiv}}} = \frac{1}{R} + \frac{1}{R_B}. \tag{2.5}$$

From these equations one can find the resistance of the voltmeter

$$R_B = R_{\text{equiv}} \frac{R}{R - R_{\text{equiv}}}. \tag{2.6}$$

Report the calculated values of the input resistances for the digital and standard voltmeters. If you get a negative value for R_B it is probably because you did not measure with sufficient precision the value of R, the approximately 100 kΩ resistor. Always remember to turn off the meters after the measurements. The meters use dry batteries with limited lifetimes.

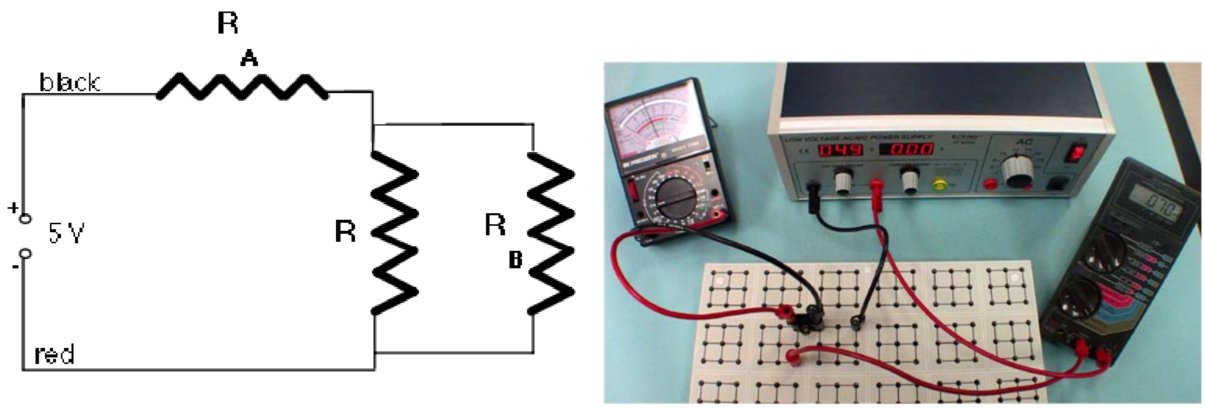

Figure 2.6: **Ohm's law circuit.** This is the same circuit as in Fig. 2.5

Table 2.5: Ohm's law measurements

	Potential (V)	Current (A)	R_{100} (Ω)	R_{equiv} (Ω)	R_B (Ω)
Digital meter					
Standard meter					

2.3 Report

In your own words explain:

- when it is practical to connect resistances in series and when in parallel.
- when the internal resistance of a meter is important, how it may affect the measurements and when it can be ignored.
- which meter is a better one?

Lab 3

Charging and Discharging Capacitors

3.1 Introduction

In this experiment you will measure the rates at which capacitors in series with resistors can be charged and discharged. The time constant RC will be found.

3.1.1 Charging a capacitor

Consider the series circuit shown in Fig. 3.1. Let us assume that the capacitor is initially uncharged. When the switch S is open there is of course no current. If the switch is closed at $t = 0$, charges begin to flow and an ammeter will be able to measure a current. The charges move until the potential across the capacitor plates is equal the potential between the battery's terminals. Then the current ceases and the capacitor is fully charged.

The question arises on how does the current in the circuit vary with time while the capacitor is being charged. To answer this, we will apply Kirchhoff's second rule, the loop rule, after the switch is closed

$$\varepsilon - iR - \frac{q}{C}, \tag{3.1}$$

where q/C is the potential difference between the capacitor plates. We can rearrange this equation

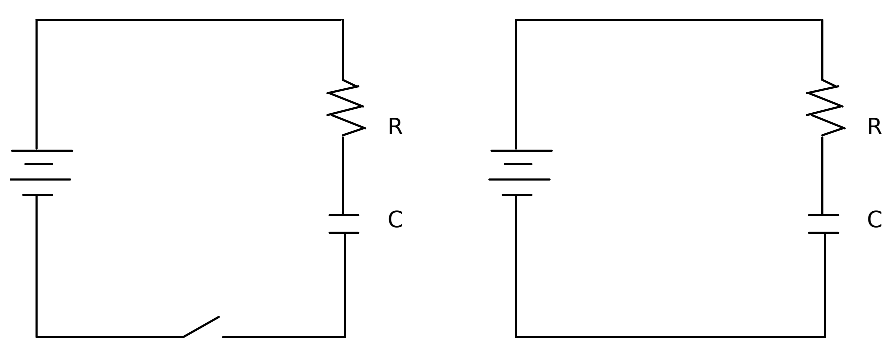

Figure 3.1: **Capacitor and resistor in series.** The left figure represents the circuit before the switch is closed, and the right after the switch is closed at $t = 0$.

as

$$iR + q/C = \varepsilon. \tag{3.2}$$

The above equation contains two variables, q and i, which both change as a function of time t. To solve this equation we will substitute for i

$$i = \frac{\mathrm{d}q}{\mathrm{d}t} \tag{3.3}$$

$$\varepsilon = R\frac{\mathrm{d}q}{\mathrm{d}t} + \frac{q}{C}. \tag{3.4}$$

This is the differential equation that describes the variation with time of the charge q on the capacitor shown in Fig. 3.1. This dependence can be found as follows. We will rearrange the equation to have all terms involving q on the left side and those with t on the right side. Then we will integrate both sides

$$\frac{\mathrm{d}q}{q - C\varepsilon} = -\frac{1}{RC}\mathrm{d}t \tag{3.5}$$

$$\int_0^q \frac{\mathrm{d}q}{q - C\varepsilon} = -\frac{1}{RC}\int_0^t \mathrm{d}t \tag{3.6}$$

$$\ln\left(\frac{q - C\varepsilon}{-C\varepsilon}\right) = -\frac{t}{RC} \tag{3.7}$$

$$q(t) = C\varepsilon\left(1 - e^{-t/RC}\right), \tag{3.8}$$

where e is the base of the natural logarithm. To find the current $i(t)$ we will substitute for q in Eq. (3.3) using Eq. 3.8. The derivation of i is

$$i = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{\varepsilon}{R}e^{-t/RC}. \tag{3.9}$$

Plots of the charge and the current versus time are shown in Fig. 3.2. The charge is zero at $t = 0$ and approaches the maximum value of $C\varepsilon$. The current has the maximum value of $I_0 = \varepsilon/R$ at $t = 0$ and decays exponentially to zero as $t \to \infty$. The product RC appears in both equations and has the dimension of time. RC is called the time constant of the circuit and is represented by the symbol τ. It is the time in which the current in the circuit has decreased to $1/e$ of the initial value. Likewise, in a time τ the charge increases from zero to $C\varepsilon(1 - e^{-1})$.

The potential across the resistor will change as

$$V_R = iR = \varepsilon e^{-t/RC} = \varepsilon e^{-t/\tau} \tag{3.10}$$

and across the capacitor as

$$V_C = \frac{q}{C} = \varepsilon\left(1 - e^{-t/RC}\right) = \varepsilon\left(1 - e^{-t/\tau}\right). \tag{3.11}$$

Both functions change in time as exponential functions with the time constant $\tau = RC$.

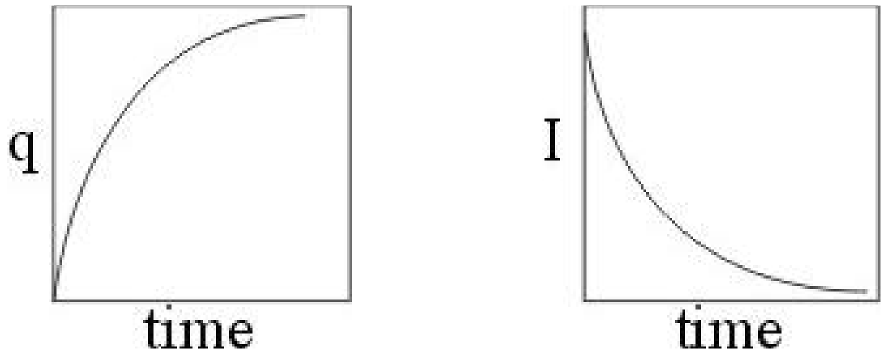

Figure 3.2: **Charging of a capacitor.** The charge (left) and the current (right) of a charging capacitor.

3.1.2 Discharging a capacitor

Assume that the capacitor in Fig. 3.1 is fully charged and the potential across the capacitor is equal that of the battery. At time $t = 0$ the switch is thrown from a to b so that the capacitor can discharge through resistor R. Substituting $\varepsilon = 0$ in Eq. (3.4) we can write the discharging equation:

$$R\frac{\mathrm{d}q}{\mathrm{d}t} + \frac{q}{C} = 0. \tag{3.12}$$

The solution for this equation is

$$q(t) = C\varepsilon e^{-t/RC} = q_0 e^{-t/RC} = q_0 e^{-t/\tau}. \tag{3.13}$$

The current can be obtained by differentiating,

$$i(t) = \frac{\mathrm{d}q}{\mathrm{d}t} = -\frac{\varepsilon}{R}e^{-t/RC} = -I_0 e^{-t/\tau}. \tag{3.14}$$

The minus sign indicates that the direction of the discharge current is in the direction opposite to the charging current. Both functions, $q(t)$ and $i(t)$, decay exponentially with the same time constant $\tau = RC$.

The potential V_R across the resistor is given by

$$V_R = iR = -\varepsilon e^{-t/\tau} \tag{3.15}$$

and the potential across the capacitor, V_C, changes in time as

$$V_C = \frac{q}{C} = \varepsilon e^{-t/\tau}. \tag{3.16}$$

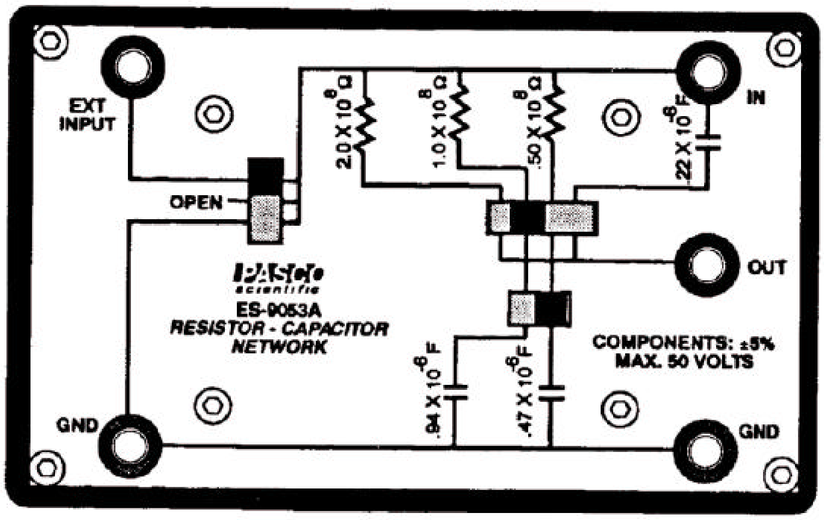

Figure 3.3: **Resistor-capacitor network.** The resistor-capacitor circuit used in Lab 13.

3.2 Procedure

The time constant τ may be determined experimentally either during charging or discharging of the capacitors. You will use the R-C network shown in Fig. 3.3. The switches allow you to select different combinations of resistors and capacitors. The positions of the switches shown in Fig. 3.3 result in the RC circuit with $R = 1.0 \times 10^8\ \Omega$ and $C = 0.47 \times 10^{-6}$ F, see Fig. 3.4.

1. To charge the capacitor you will use a DC Power Supply, Pasco model 9049. **Select the** 30 V **range**. The R-C network is designed to work only within this range. The "VARIABLE" control turns the power supply on and varies the voltage from 0 to 30 V. The output voltage can be read on the bottom scale of the meter. The output terminals have different colours, black for negative terminal and red for positive. **The green terminal is only for 500 and** 1000 V **ranges - do not use it!!**

2. Set the circuit as shown in Fig. 3.5. Select a resistor R and a capacitor C. Attach the electrometer to measure the voltage across the capacitor. Close the switch and start the timer. At regular time intervals record the capacitor voltage.

3. Charge the capacitor to the initial potential of 30 V. Disconnect the power supply and close the circuit by sliding the switch to the bottom position. Simultaneously start the timer. Use the electrometer to measure the voltage across the capacitor at the same time intervals.

4. Repeat the charging and discharging for other values of R and C.

5. Repeat the experiment by charging and discharging capacitors, but this time measure the voltage across the resistor. According to Ohm's law, potential is proportional to resistance multiplied by current. Hence, the potential across the resistor is proportional to the charging current.

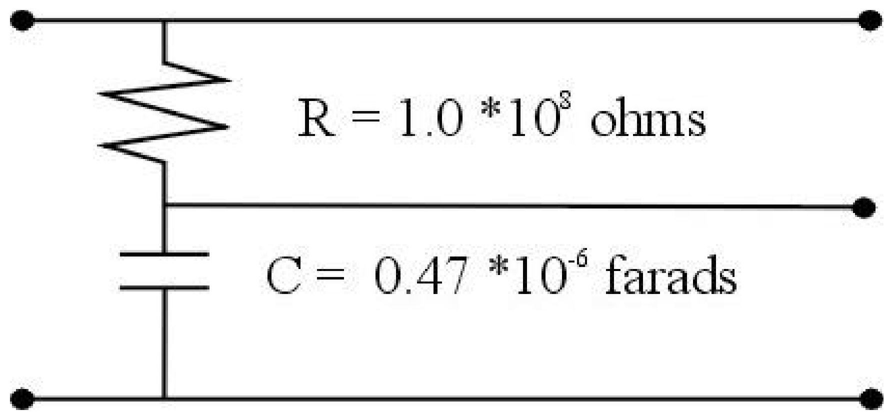

Figure 3.4: **RC circuit corresponding to the positions of the switches in Fig. 3.4.**

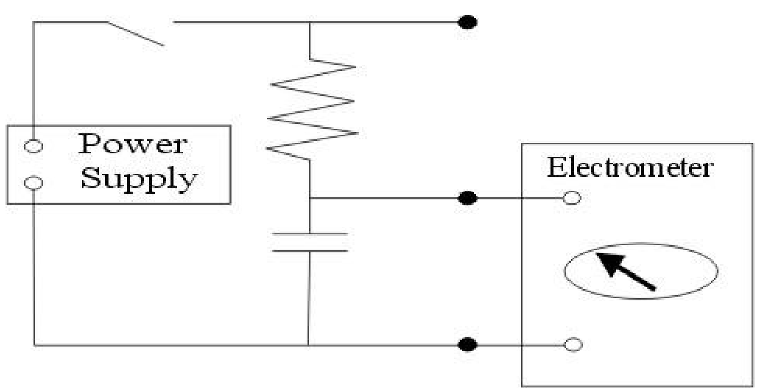

Figure 3.5: **Experimental setup to charge a capacitor.**

3.3 Report

Plot the logarithm of the capacitor voltage during charging versus time for different combinations of R and C. Your data should form straight lines. Use a fitting program to find the slopes of those lines. (Remember to express time in seconds, resistance in ohms and capacitance in farads). How do the experimental slopes compare with the expected values for τ?

Plot the capacitor voltage during discharging the capacitor versus time. Again use the logarithmic function to determine the slope. Does the time constant τ remain the same for discharging and for charging capacitors?

Determine the relationship between the current, the capacitor charge and the capacitor potential.

Lab 4

Current and Resistance

4.1 Introduction

This is a simple experiment in which you will investigate the relationship between potential, current and resistance for three different materials. You will learn that not all materials follow the Ohms law.

For a metallic resistor kept at a fixed temperature an increase in the voltage results in a corresponding increase in the current. This dependence is given by the Ohms law:

$$V = IR. \tag{4.1}$$

Deviations from this linear relationship are expected when the temperature is increased. For metals, the temperature dependence of resistance in given by

$$R(T) = R(T_0)[1 + \alpha(T - T_0)], \tag{4.2}$$

where $R(T_0)$ is the resistance at room temperature T_0, $R(T)$ is the resistance at temperature T, and α is the thermal coefficient of resistivity. Different metals have different values of α. When the temperature of the conductor is increased due to thermal heating, the V vs. I plot is no longer a straight line.

For semiconductors and isolators the voltage-current relationship is different from that given by Eq. (4.1). There are theoretical models that explain how the voltage changes with the current flowing through various gases, liquids and semiconductors. These models are complicated and their understanding is beyond the scope of this course. However, even without deep understanding of relevant theories you should be able to recognize different $V(I)$ dependencies and identify mechanisms responsible for conductivity.

The first light bulb built by Thomas Edison had a carbon filament. Carbon is a semimetal and its resistance decreases slightly with increasing temperature. Thus, for a carbon resistor, when the temperature is increased, the plot voltage versus current slightly departs from a straight line. This property of carbon that allows it to maintain approximately the same value of resistance at various temperatures is utilized by the electronic industry which often uses this material to manufacture resistors.

Gases conduct electricity only after atoms become ionized. Ionized atoms and free electrons accelerate in the electric field, collide with other atoms, and in the course of these collisions secondary electrons and ions are formed. Motion of the electrons and ions is responsible for the flow

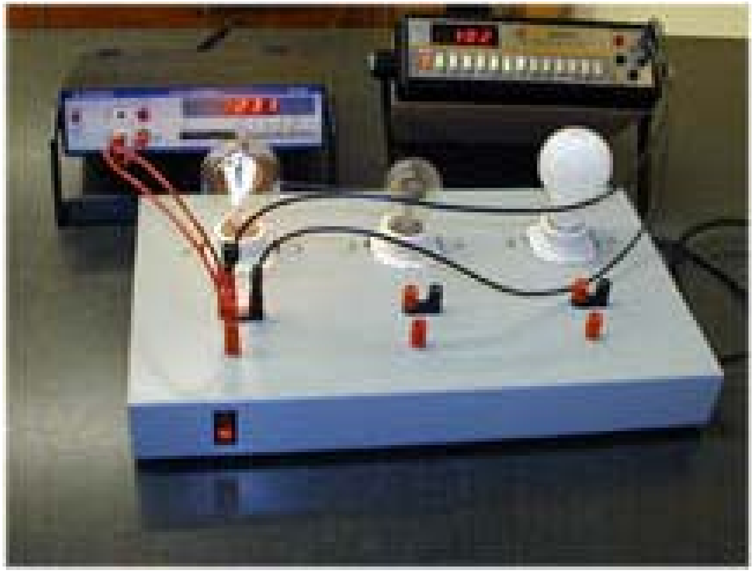

Figure 4.1: **Experimental setup.** Three light bulbs with different filaments are used in this experiment.

of the current between the electrodes. For a given separation of the electrodes, d, the maximum voltage that can be applied without causing a discharge depends on the dielectric strength. The dielectric strength for dry air is about 3×10^6 V/m. If the applied electric field, $E = V/d$, exceeds the dielectric strength, the insulating properties break down and the medium begins to conduct. Of course, we do not want to work with potentials on the order of million of volts. To generate electric fields that would exceed the dielectric strength of the material and use reasonably low voltages, the distance between the electrodes must be reduced. For example, when that distance is reduced to less than 1 mm, the voltage required to start the discharge is reduced to a manageable value of less than 1000 V. Adjusting the pressure of the gas between the electrodes could further reduce this potential. This property is often used in voltage regulators.

4.2 Procedure

1. On the lab desks you will find metal boxes, each with three light bulbs, as shown in Fig. 4.1. The Victorian bulb on the left side of the box has a carbon filament, the lamp at the center, with two horizontal flat electrodes is the neon lamp, that on the right is the tungsten lamp. Make sure that the power switch on the front face of the box is in the OFF position. Next, plug in the power cord attached to the box into an outlet controlled by a variac, see Fig. 4.2.

2. Connect an ammeter and a voltmeter to one of the lamps. The ammeter should be connected in series connect the ammeter to the red posts on the box. The voltmeter should be connected in parallel, between the red and black posts, as shown in Fig. 4.1. Make sure that the instruments are set to measure AC current and potential, respectively. If you will use desktop

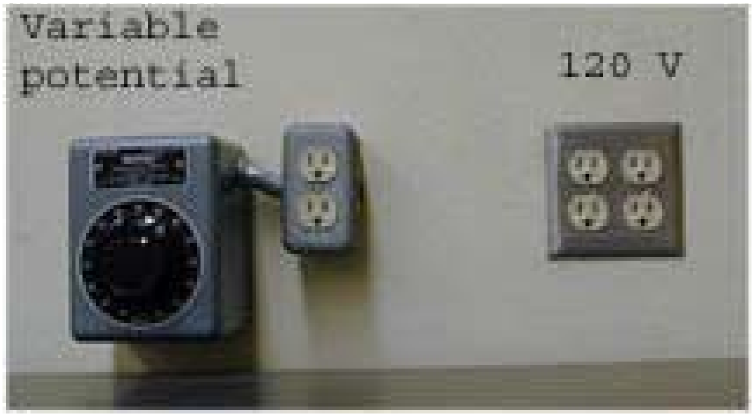

Figure 4.2: **Electrical outlets.** Use the electrical outlet with the variac.

multimeters, plug them into the 120 V outlets, not into the outlets of variable potentials! Ask the assistant to check the connections and only then turn the switch ON.

3. Increase the potential by rotating the large knob on the variac clockwise. For the carbon and the tungsten filament lamps initial increments should be small, about 1-2 volts, but after you exceed 10 V increase the step to about 5–10 V. Even if you turn the variac all the way to zero it will still provide some non-zero voltage, you make check it by increasing the sensitivity of the voltmeter. For each potential record the value of the current in proper units. For each lamp, you should record about twenty pairs of data points. IMPORTANT: remember to reduce the voltage to zero and to turn the power off before you connect the wires to another lamp. The neon lamp will not conduct electricity until you reach about 50 V, make several readings around this value, and then increase the potential in about 5–10 V increments. Do not increase the potential above 100 V because the lamps will be too bright.

4.3 Report

For each lamp plot voltage vs. current. Can the data be approximated by a straight line? Explain. Calculate resistance for each lamp. Plot resistance versus voltage. Observe that resistance significantly increases for the tungsten filament, slightly decreases for carbon and follows an exponential decay for the neon lamp. Explain these dependencies. Use Eq. (4.2) to estimate the temperature of the tungsten filament at the maximum potential. Assume that the thermal coefficient of resistivity for tungsten is 0.0045 /°C, and $T_0 = 20$ °C. Explain why the resistance of metals increases with increasing temperature. Suggest a mechanism that would explain the observed decrease of the resistance of carbon filament with increased temperature. Repeat for the neon lamp.

Lab 5

Inductance

5.1 Introduction

The basic relationship between the voltage across an inductor and time rate of change of the current through the inductor is given by

$$V = -L\frac{\Delta I}{\Delta t}. \tag{5.1}$$

If we set up the circuit as shown in Fig. 5.1 with a triangular wave from the function generator applied to an inductor of inductance L in series with a resistor R, the voltage at B with respect to ground is given by Eq. (5.1).

The function generator can produce waves of various shapes. We will use a triangular wave form of the type shown in Fig. 5.2. From a to b, the slope is

$$\frac{\Delta I}{\Delta t} = \frac{-2I_0}{T/2} = -\frac{4I_0}{T}. \tag{5.2}$$

From b to c, the slope is $+4I_0/T$. Thus at point b, the slope changes by $8I_0/T$. From Eq. 5.1 we see that this will lead to a change in voltage across the inductor of

$$\Delta V = -L\frac{\Delta I}{\Delta t} = -L\frac{8I_0}{T}. \tag{5.3}$$

A change in voltage of similar magnitude will occur at points a and c producing a square wave as shown in Fig. 5.3.

Thus by measuring ΔV for different values of maximum current, I_0, and the period, T, we can verify the linear relationship indicated by Eq. (5.1) and obtain the inductance L.

5.2 Procedure

1. Set up the circuit as shown in Fig. 5.1 with a 330 Ω resistor. Adjust the function generator to give a 10 V peak-to-peak triangular wave. Please note that this voltage is distributed across the resistor, R, and the inductor, L. Set the function generator to give the frequency of 100 Hz. Observe the signal on channel 1 of the oscilloscope. If the measured frequency is less than 100 Hz adjust the function generator. The settings on the oscilloscope for channel 1 should be: sweep 2 ms, and 5 V/div.

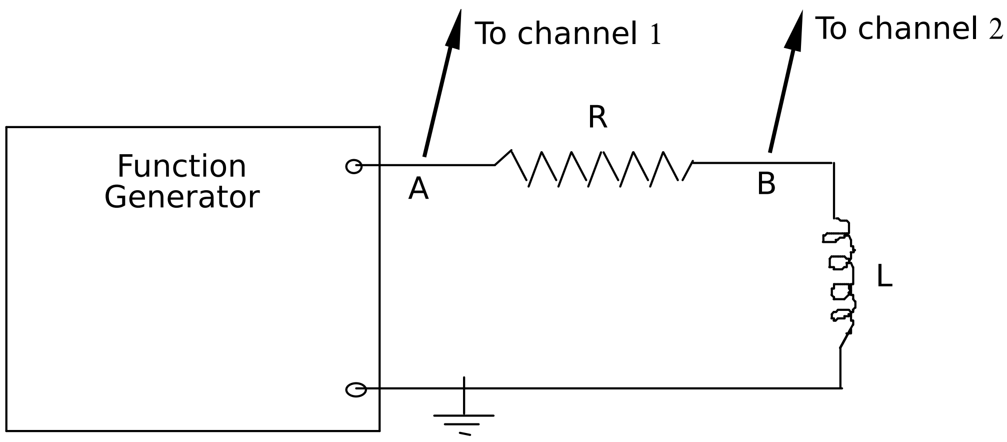

Figure 5.1: **Experimental setup.** The function generator supplies the triangular wave of the shape shown in Fig. 5.2 through the circuit.

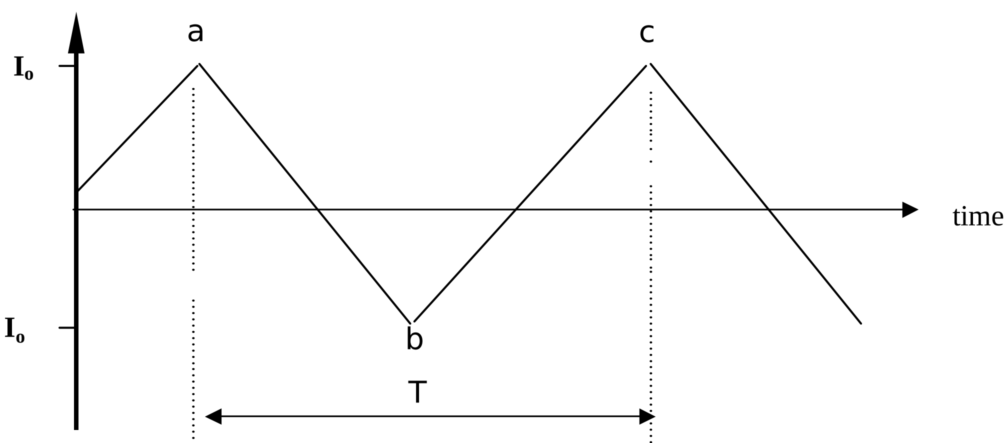

Figure 5.2: **Triangular waveform of period T.** This waveform has two values of slope, $\Delta I/\Delta t$, one for the decreasing potential and another for the increasing potential.

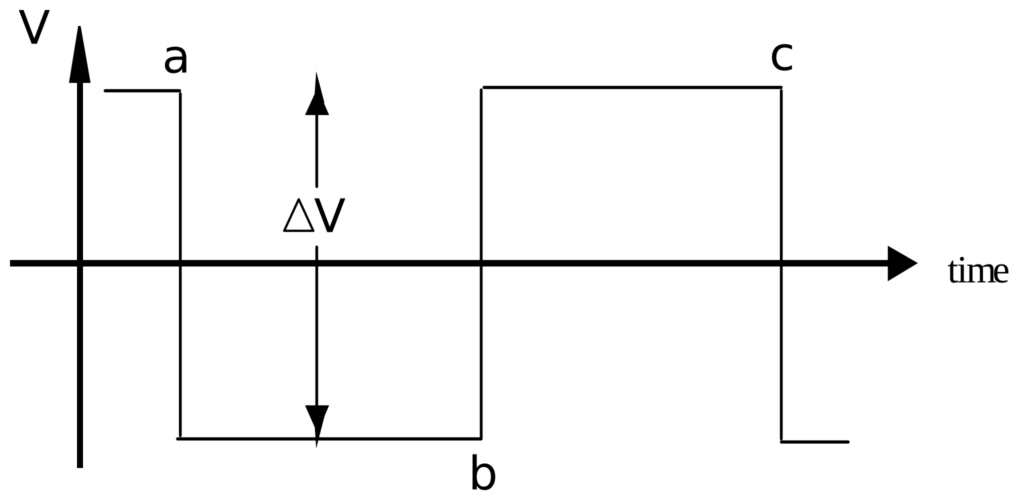

Figure 5.3: **Induced square wave potential.** A triangular wave input leads to a square wave potential.

2. The maximum current, I_0, is found by measuring the voltage change across R,

$$I_0 = \frac{V}{R}. \tag{5.4}$$

   V is the maximum potential delivered by the function generator. If you followed the instructions given above you have adjusted it to 5 V (half of the peak-to-peak value), and $R = 330\ \Omega$.

3. Since we now know I_0, in order to verify Eq. (5.1) you need to measure the induced potential, ΔV. Unfortunately, the waveform observed on channel 2 (from point B in the circuit) does not look like that shown in Fig. 5.3. Instead a waveform, which is illustrated in Fig. 5.4 is usually observed. This is caused by the resistance of the wire in the inductor, R_L. The potential drop across that resistance is independent of frequency and is given by

$$\delta V = 2 I_0 R_L. \tag{5.5}$$

   You will measure the potential, δV, from the scope and compute the resistance R_L. Compare this value with the resistance measurements of the inductor made with an ohmmeter.

4. Measure the potential ΔV from the screen of the oscilloscope. Of course, use channel 2. Change the frequency from 100 Hz to 1000 Hz. Potential ΔV varies with frequency, and you may have to adjust both the time and voltage settings for channel 2. Record your data in the table below.

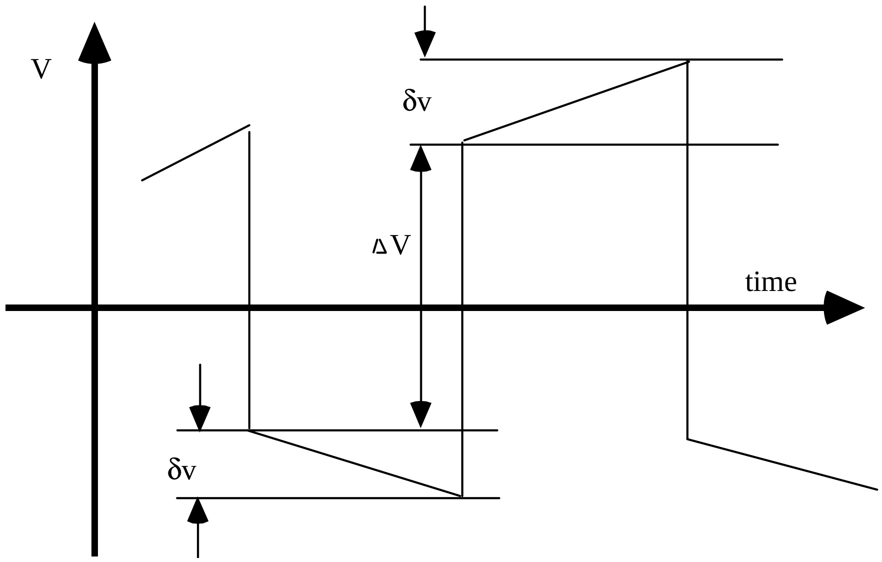

Figure 5.4: **Observed waveform.**

ΔV (V)	δV (V)	frequency (Hz)	$I_0 f$ (A/s)
		100	
		200	
		300	
		400	
		500	
		600	
		700	
		800	
		900	
		1000	

5. Solenoid inductance, L, can be calculated from

$$L = \mu_0 \frac{N^2 A}{l}, \tag{5.6}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Tm/A, N is the number of turns, A is the cross section area and l is the length of the solenoid. To determine N, count the number of loops in the top layer and multiply it by 5, because there are 5 layers of wire. Measure the radius and length of the solenoid and then calculate L. Express L in henrys.

5.3 Report

1. In the introduction discuss Faradays law of induction and Lenzs law. Explain self-inductance. What is the unit of L?

2. Plot ΔV versus $I_0 f$. The resulting graph should be a straight line with a slope of $8L$. Determine the inductance, L, of the coil. Discuss the error. Compare experimental and theoretical (Eq. (5.6)) values for L.

3. Compare resistance R_L of the coil measured using an ohmmeter with the value obtained from Eq. (5.5).

Lab 6

Measurement of the Mass of an Electron

6.1 Introduction

An electron travelling with a speed, v, perpendicular to a uniform magnetic field, B, will experience a force, F, with a magnitude,

$$F = evB, \tag{6.1}$$

where e is the charge of the electron. The direction of the force is perpendicular to the plane defined by the direction of v and B. The force is always perpendicular to the direction of motion of the electron. The electron moves in a circular path of radius r, with the magnetic force supplying the centripetal force. That is

$$F = evB = F_c = m\frac{v^2}{r}, \tag{6.2}$$

where m is the mass of the electron. Solving for v, we have

$$v = \frac{eBr}{m}. \tag{6.3}$$

The electron speed v is acquired by accelerating the electron through a potential difference,

$$eV = \frac{1}{2}mv^2. \tag{6.4}$$

Substituting for v we find

$$eV = \frac{1}{2}m\left(\frac{e^2B^2r^2}{m^2}\right) \tag{6.5}$$

which reduces to

$$\frac{e}{m} = \frac{2V}{B^2r^2}. \tag{6.6}$$

Hence, by knowing or measuring e, V, B, and r, the mass of the electron can be computed.

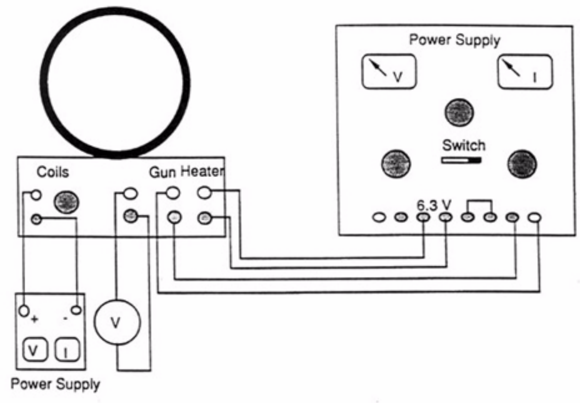

Figure 6.1: **Experimental setup.** Schematic of the connections between the power supply, heater and coils.

6.2 Procedure

The apparatus used in this experiment consists of a cathode tube, Helmholtz coils, two power supplies and an ammeter. The cathode ray tube is filled with hydrogen gas at low pressure of about 0.01 mm Hg. In some tubes, hydrogen gas is replaced by mercury vapor. Electrons collide with hydrogen, ionize them, and when atoms recombine with stray electrons, the characteristic green light is emitted. The emission occurs only at the points where ionization took place; therefore, a beam of electrons is visible as a luminous streak in a dark room.

The tube used in the experiment has been designed in such a way that the radius of the circular path of the electron beam can be conveniently measured. The electrons are emitted by the indirectly heated cathode, and are accelerated by the applied potential V between the filament and the anode. The cathode and the anode are constructed in such a way that only a narrow beam is allowed to pass the anode. Outside the anode, the electron beam moves with constant speed. When the beam is inside a magnetic field, it will move along the circle with a diameter given by Eq. (6.2).

A pair of Helmholtz coils produce an almost uniform magnetic field near the center of the coils which can be given by

$$B = \frac{8\mu_0 NI}{\sqrt{125}a}, \tag{6.7}$$

where B is the magnetic field in teslas, N is the number of turns of wire in each coil, I is the current through the coils in amperes, and a is the mean radius of each coil in meters, which is equal to the distance between the coils. In the Helmholtz coils used in the experiment the number of turns is 130 and the radius is 15 cm.

1. Connect the heater and the anode of the vacuum tube to the high voltage power supply. The heater should be connected to a 6 V terminal. The anode voltage should be between 150 and 300 V. The coils have their own power supply with the voltage set to 12 V. Check the wiring (Fig. 6.1) and if you have any questions, ask the assistant for help.

2. Turn on the power. As soon as the cathode starts to glow, increase the anode voltage so that the beam will be as sharp as possible. **Do not increase the potential above** 300 V**.**

3. Turn on the power supply of the Helmholtz coils. Select a value of the current in the coils; it should be between 0.5 and 2 A. Compute the magnetic field. Measure the diameter of the circular beam and record the current in the coils and the accelerating potential between the anode and the cathode. Increase the accelerating potential and record the beam radius. Repeat this procedure for 4 different accelerating potentials. To reduce the experimental error, read the beam diameter several times. Record your results in the following table.

Experiment 9 measurements.

Coil current (A)	B (T)	Anode voltage (V)	Radius of circle (m)	e/m (C/kg)	m (kg)

4. Repeat the above procedure with a different value of the coil current. You should have at least 10 different readings for different combinations of experimental parameters. From Eq. (6.6) find the e/m ratio and then calculate the mass of the electron, assuming that its charge is known and equals $e = 1.602 \times 10^{-19}$ C.

5. Since you have at least 10 experimental data points for m you can determine the mean value, $< m >$, and the standard deviation, Δm. The mean value and standard deviation are defined as

$$< m > = \frac{\sum_n m_n}{N} \tag{6.8}$$

$$\Delta m = \sqrt{\frac{\sum_n (m_n - < m >)^2}{N-1}}, \tag{6.9}$$

where m_n are the measured values, n is the running number which varies from 1 to N, and N is the total number of points. Within the error, the mean value should be equal the expected textbook value, if not, discuss any discrepancy.

6.3 Report

Calculate the mean value of mass and estimate the error. In the report, discuss the following topics:

1. The e/m ratio can also be found from the method used by Thompson. Explain the principle difference between each method.
2. Discuss the effect of the earth's magnetic field on the result of this experiment. Could you correct this effect? How?
3. Compute the velocities of electrons for all accelerating voltages used.
4. (For 20481 and 20484) Use the Biot-Savart law to derive Eq. (6.7) for the magnetic field. Find the change in B as you move a distance r from the center between the coils.

Lab 7

Magnetic Field of a Solenoid

7.1 Introduction

A solenoid is a long, tightly wound coil carrying electric current. The magnetic field generated by the solenoid is very strong inside the coil. Outside of the solenoid the magnetic field is essentially zero, see Fig. 7.1.

Using Ampere's law one can derive the magnetic field inside the solenoid to be

$$B = \mu_0 n I, \tag{7.1}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Wb/Am, n is the number of turns per unit length, and I is the current. For solenoids that are not very long, we use a more accurate formulae for the magnetic field:

$$B = \mu_0 n I \frac{L/2}{\sqrt{(L/2)^2 + R^2}}, \tag{7.2}$$

where L is the length and R is the radius of the solenoid.

In this experiment you will measure the magnetic field using a Hall probe. Hall discovered that when a current flows through a conductor placed inside a magnetic field, a charge separation is observed on opposites sides of a conductor. The electric current I can be treated as a number of electric charges moving along the conductor. When a moving charge is placed inside a magnetic field, $\vec{B}$, the field exerts a force, $\vec{F}$, that is proportional to the velocity of the charge,

$$\vec{F} = q\vec{v} \times \vec{B}. \tag{7.3}$$

The direction of the force is given by the right-hand rule. For a sample where the charge carriers have positive signs, the force given by Eq. (7.3) results in charge separation and the top of the conductor becomes positively charged. The electric field associated with this effect gives rise to a potential difference between the top and the bottom of the conductor. The potential difference is given by

$$V = Ed \tag{7.4}$$

where d is the thickness of the conductor. Measurements of the Hall effect provide information on the sign of the charge carriers. If the conductor carries a known current, the induced electric potential, V, is proportional to the magnetic field, so that the Hall potential provides a simple way to measure the magnetic field.

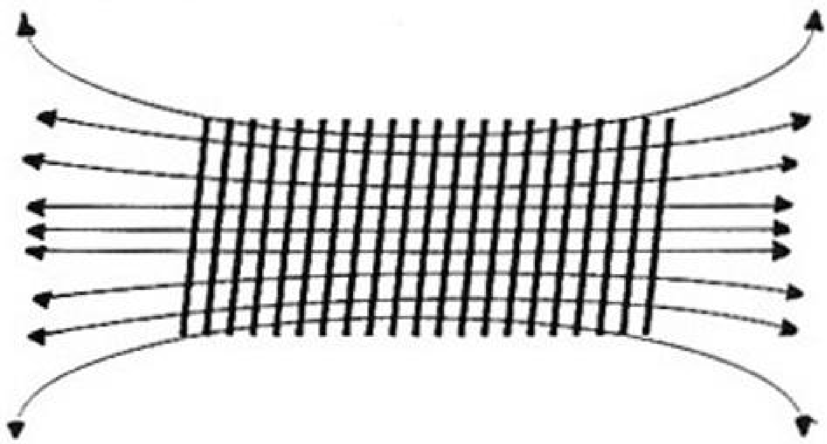

Figure 7.1: **Magnetic field of a solenoid.** The magnetic field of a solenoid is much stronger inside than outside the solenoid.

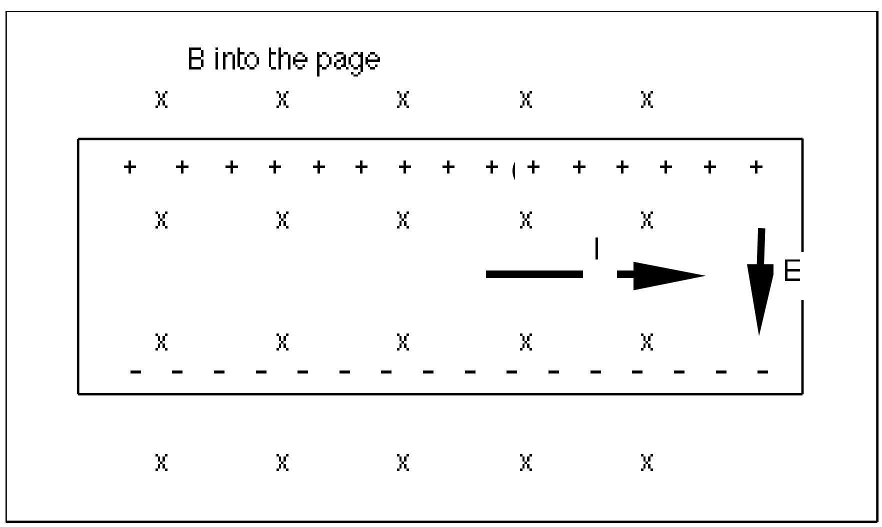

Figure 7.2: **Hall effect.** The magnetic force on the conductor with positive charge carriers moving to the right, will cause a drift of the charges toward the top of the conductor resulting in a downward electric field, E.

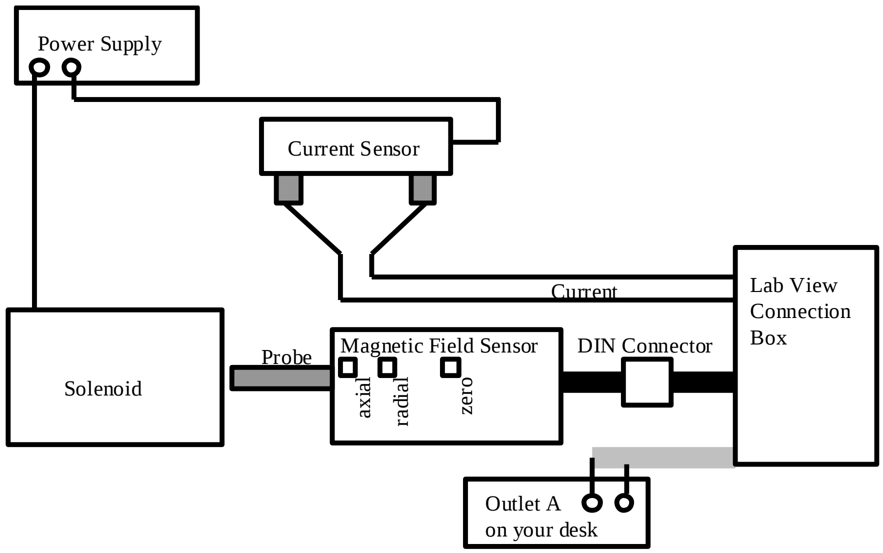

Figure 7.3: **Experimental setup.** Electrical connections for the Hall effect experiment.

7.2 Procedure

The Hall potential is usually small and has to be amplified before it could be measured by a standard meter. Measurements of magnetic field are difficult by traditional methods. In the first step you will use a voltmeter to measure the Hall potential and get a general sense how difficult such measurements could be. Later you will repeat the same experiment by using a computer with LabView interface and software.

When you come to the lab you should find the equipment assembled for the measurements. It is possible that some parts had been disconnected, therefore, check the diagram in Fig. 7.3 and connect the wires appropriately.

1. The solenoid should be connected in series with a power supply and the Current Sensor. The original sensor has been modified, and it is mounted onto an aluminum block. The 1 Ω resistor can dissipate 5 W of power, which means that it can carry a 5 ampere current. The two posts on the Current Sensor should be connected to channel 0 in the metal interface box with the National Instruments logo on it. To do this use a set of black and red posts the box. They are marked A. **Do not open the box**, the wires have been secured to the posts inside, but if you suspect that there is something wrong with those connections ask the instructor for help.

2. There is a black cable and an additional pair of leads in a gray shield coming out of the LabVIEW box. Connect the leads in the gray cable to the outlet of another power supply on your desktop. This power supply should be set to 10 V DC and there will be no need to adjust it. Move the switch to the Axial position. Now you will be able to measure axial magnetic field. Before the measurements you may have to zero the sensor. Place the tubular end of the sensor into a short metal sleeve and press Zero. Next, adjust the sensitivity of the probe by moving another switch to the X1 position. At this switch position 1 V in the output

corresponds to 100 Gs. Place the sensor inside the solenoid and make sure that the sensor is near the center of the solenoid.

3. Disconnect the sensor from the LabView box and plug it into a multimeter set to measure DC volts. Slowly increase the current through the solenoid to 1.0 A, and record the value of the current and the Hall potential, which is proportional to the magnetic field inside the solenoid. Repeat for 2.0, 3.0, 4.0, and 5.0 A currents. Unplug the sensor from the voltmeter and plug it into the LabView Connection Box. Now, you will repeat the same measurements and the use of the computer will allow you to take hundreds of measurements in a relatively short time.

4. Turn the computer on and log on. On the desktop you will find icon Shortcut to Lab12, double click on it. It is possible that a LabVIEW window will appear asking you to register the software — click Cancel and later OK, ignore the warnings. A window like that shown in Fig. 7.4 should appear. Make sure that Device is set to **1** and Time to **1**. Channels should display **0:1**. Write the file name in the black window near the left top corner of the screen. I suggest that you use your last name with extension *xls* or *xlsx*. Your data will be saved in the folder *DataLab12* on the desktop. Click on the arrow at the top of the window, or go to the pull down menu, select *Operate* and then *Run*. Alternatively you could type *CTRL-R*.

5. **Do not change the voltage on the power supply connected to the magnetic sensor. It should be set to** 10 V **DC. DO NOT CHANGE THAT SETTING — YOU MAY DAMAGE THE SENSOR!** Slowly increase the voltage on the power supply connected to the solenoid, at a rate less than 1 Volt per second and observe the display. The line displaying channel "0" should rise slowly and finally approach level 5. When it is equal 5 reduce the voltage to zero. Again, do it slowly. The computer reads the data every second, and you need enough data to get a reasonable fit. The second line in the display corresponds to the signal from the Hall probe. That signal has been amplified, but it still very small and the line depicting the magnetic field should probably vary between 0 and 2.5. Readings below zero or above 2.5 V indicate that something is wrong with the sensor. Most likely you need to zero the sensor. Remove it from the solenoid and place the end of the sensor (the black tube) inside a metal pipe and then press button zero. It is also possible that the wires are crossed and you may need to swap them to get positive values. When you have recorded enough data, stop the experiment by pushing the STOP button.

6. Go to *START*, select *Microsoft Office*, and then launch *Excel*. When the spreadsheet program appears on the screen go to *File* and *Open*. Select the file you just saved in LabVIEW. The data were saved in the folder *Datalab12* on the desktop. If you saved your data file with extension *xls* or *xlsx*, Excel will recognize that format and you should see the icon depicting your document. Otherwise, you may have to go to *Type of Files* and select *All Files*. Then double click on your document and Excel will import your data. The *Text Wizard* window will appear and you should follow the instructions. If you used the military time, all data will appear in the spreadsheet. The spreadsheet is organized as follows. The first column is the date of the experiment, the second is the time the data were recorded, the third is the current in the solenoid, and the last column is the magnetic field. In the experiment we measure the voltage across the 1 Ω resistor inside the Current Sensor. Because it is a 1 Ω resistor, the voltage across it gives the value of the current in the resistor. The current sensor

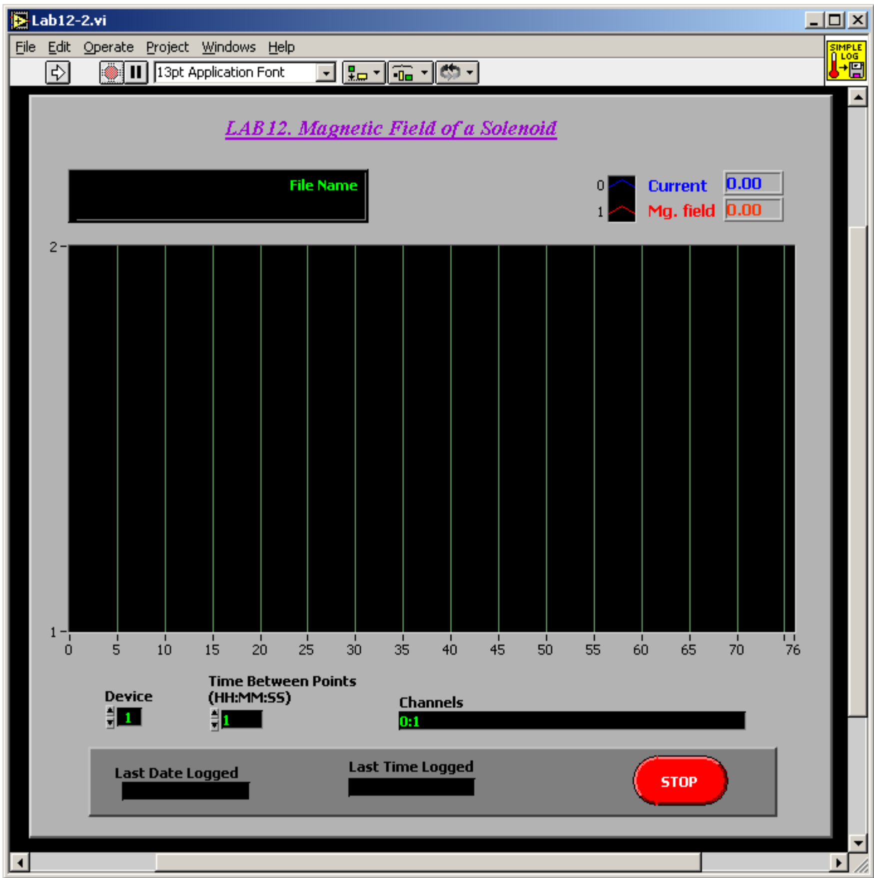

Figure 7.4: **Labview screenshot.** The Labview control panel for measuring the Hall effect.

is connected in series with the solenoid, which means that the same current flows through the solenoid. The Magnetic Field Sensor has been designed to give output voltage proportional to the magnetic field. 1.0 V **corresponds to 100 Gauss or** 100×10^{-4} T. T is the unit of the magnetic field in the SI unit and stands for Tesla. Change the values of the magnetic field, which are in volts, to read the magnetic field in T.

7. Select the third and fourth columns and click on *Chart Wizard* (the symbol with 3 color bars). Select XY graphs with the current on the x-axis. The data should lie along a straight line.

8. You may now go back to LabVIEW and restart the experiment. Increase the solenoid current slowly to 5 A and then decrease it slowly, repeat that cycle several times. Save the data and display them as before using Excel. If the data are not along the straight line it means that the sensor drifted and needed to be zeroed again. You do not have to repeat the experiment, if you have enough data points, you may just delete bad data. You will quickly identify the bad data points in the fourth column because they will have negative values or values exceeding 2.5.

9. Now you should be ready to fit the data to a straight line. The following comments are valid for MS Excel 2000; for other versions the format is different, but the main procedure remains the same. Click once on the graph and go to *Chart* in the main menu. Pull *Chart* down to *Add Trendline* and select linear regression. Click on *Options* and select *Display Equation on Chart* and *Display R-Square value on Chart.* Click OK and examine the graph and the quality of the fitting. If the R-value is small, you may have to repeat the measurements. R greater than 0.95 usually indicates a very good fit. If you are satisfied with the quality of the data, label the axes and select a title for the graph. To do this go to *Chart* and *Chart Options*. Print the graph. Remember to log off when you finished the experiment. Go to *START* and select *Log Off.*

10. Measure the length and diameter of the solenoid. The total number of turns is 570.

7.3 Report

In the report attach the graphs depicting the magnetic field against the current. Both graphs should be prepared by Excel and both should indicate the slopes. The first graph is for the data you took manually using a voltmeter to measure the Hall potential, and the second for data obtained directly from the LabView software. According to Eq. 7.2 the graphs should show linear dependence, and the slopes divided by the number of turns per unit length and by $(L/2)/[(L/2)^2 + R^2]^{1/2}$ should give you the value of magnetic permeability, μ_0. Compare the results obtained for the manual and the computer readings with the expected value for the empty space. You should be getting a value for magnetic permeability which is very close to the expected value.

In the introduction discuss the following topics:

1. Hall effect for a sample with negative charge carriers. Draw an illustration similar to that shown in Fig. 7.2, but for the negative charges.
2. What is the source of the magnetic field of Earth?
3. Why is the magnitude of the magnetic field increased when a piece of iron is placed inside the solenoid?

Lab 8

Superconductor

8.1 Introduction

Superconductivity was discovered by H. Kamerlingh-Onnes in 1911. Simple metals like mercury, lead, bismuth, and others become superconductors only at very low temperatures of liquid helium. Various alloys were also found to be superconductors at somewhat higher temperatures. Unfortunately, none of these alloy superconductors work at temperatures higher then 23 K. Therefore, for many years superconductivity has been merely an esoteric problem and not many scientists were interested in studying it. Then in 1986, researches at the IBM laboratory in Switzerland, discovered that ceramics from a class of materials called perovskites were superconductors at about 35 K. As a result of this breakthrough, scientists began to examine the various perovskite materials very carefully. In February 1987, a ceramic material was found that was a superconductor at 90 K. In this temperature region, it is possible to use liquid nitrogen as a coolant since nitrogen condenses to a liquid at 77 K. This is an inexpensive refrigerating fluid; and it is feasible that in the near future superconductivity will find some practical applications.

It is necessary to use quantum mechanics to explain the mechanism of superconductivity. At the present time there is no complete theory that explains superconductivity in both metals and ceramic materials. However, it may be assumed that in superconductors electricity is conducted by electrons coupled in pairs. These pairs, called Cooper pairs, are formed at temperatures below the critical temperature, T_c, and they can move through the material without loosing energy. That means that at temperatures below T_c the resistance is zero. Narrow wires could carry large currents without loss in the electric energy (the main cost of transmitting electric power at a distance). However, there is a certain maximum current, I_c, that destroys superconductive properties. At currents larger than I_c the materials stop being superconductors. The goal of this experiment is to find the critical temperature by recording the current and the temperature dependence of resistance of a superconductive disk.

The superconductors you will study have the chemical formula $YBa_2Cu_3O_x$, where x is approximately 7 or $Bi_2CaSr_2Cu_2O_9$. Because metals yttrium (Y), barium (Ba) and copper (Cu) are in the ratio 1 to 2 to 3, the former material is called a 1-2-3 superconductor. The production of 1-2-3 superconductors is very simple. Yttrium, barium and copper oxides are mixed in the correct proportion, poured into a die mold, pressurized to form a disk and fired in a furnace to a temperature of about 1700°F. The bismuth based superconductors are called 2-1-2-2 materials and are made in a similar manner. The 1-2-3 and 2-1-2-2 superconductors have different critical temperatures.

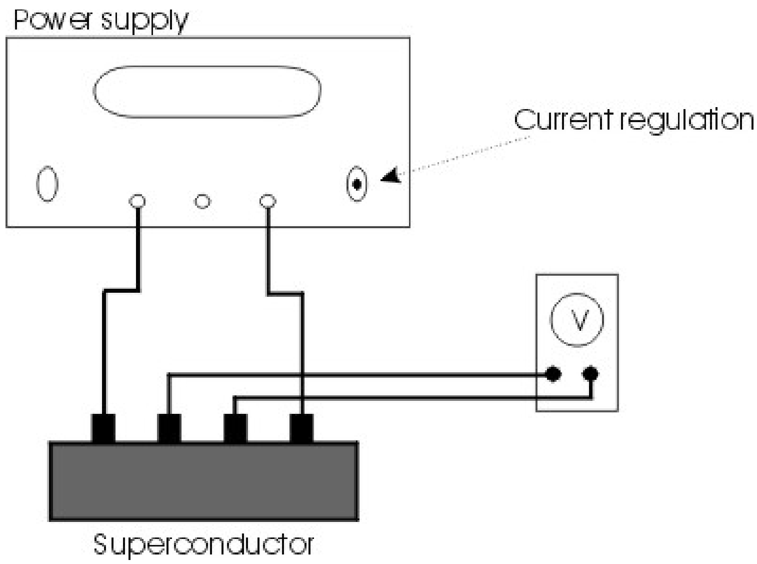

Figure 8.1: **Schematic of a four point probe.**

To measure the resistance of a ceramic material, we use the four point electrical probe. A schematic of a four point probe is shown in Fig. 8.1. This technique eliminates the effects of contact resistance. This is a very important technique, which is used in measuring resistance of biological materials, polymers and other materials. When the resistance is measured by attaching two wires to a sample, the resistance of the contacts is also measured. For metals this contact resistance is usually small and to a first approximation can be neglected. So when you measure the resistance of a 10 kΩ resistor, for example, the contact resistance of less then 1 Ω can be safely ignored. But for a 1-2-3 superconductor, the resistivity is very small and the contact resistance may appear to be larger than the effect you are trying to measure. In the four point probe the current leads are attached to the sample at different places than the wires which read the potential drop. For a sample with electrical resistance a current flowing through the sample will cause a potential drop between any two points inside the sample. This potential difference can be read by a voltmeter, and it is proportional to the product of the current and the resistance of the sample. The resistance is small; and to increase sensitivity of the voltage measurements, the current should be between 0.01 and 0.5 A. The voltmeter should have a large internal resistance to minimize the current flow through the portion of circuit comprising the voltmeter. Because there is no potential drop across the contact resistance associated with the voltage probes, only the resistance of the sample is measured.

The superconductor is placed in a metal holder to protect it from thermal shock and mechanical stresses. Six wires are attached to the cylinder. Four form the four point probe and two are connected to a thermocouple inside the device. Thermocouple wires are connected together and this joint produces a small potential drop. This voltage can be measured by any voltmeter and converted into temperature. You may use a digital voltmeter and the conversion table shown below; or a digital thermometer which will display the temperature of the superconductor in degrees Kelvin. Of course, the conversion table is built into a microprocessor, a part of the thermometer which is nothing more than a voltmeter. You will use T-type or K-type thermocouples which are made of copper and constantan, or chromel and alumel, respectively. Constantan is a copper-nickel alloy. Chromel is an alloy of Ni and Cr and alumel contains Ni and Al.

8.2 Procedure

Safety instructions

You will do the experiment at very low temperatures. Be very careful when working with liquid nitrogen. Do not touch liquid nitrogen or any object immersed in this fluid. Moisture on your fingers can freeze almost instantaneously when exposed to such low temperatures. As a result your skin may be "glued" to the metal and fingers may also freeze. When pouring liquid nitrogen be careful to prevent any splashing. Do not cover a container with liquid nitrogen in it with a tight-fitting lid. When nitrogen evaporates, the pressure inside the container may increase causing an explosion.

Do not expose the superconductor to water. After the experiment, wait for the cylinder to warm to room temperature and wipe it to remove frost or water. Later use a hair drier to ensure that it is dry. Do not increase temperature above 100°F. Store the superconductor in a box with some drying agent, like silica gel.

1. Attach two black wires to a digital voltmeter and the red wires to an ammeter and a power supply. Attach the thermocouple to a voltmeter or a digital thermometer. Set the thermocouple reader to read the T or K thermocouple. You can read the symbol of the thermocouple on the plastic connector attached to the thermocouple. Do not bend the thermocouple. Place the cylinder, with the wires attached, into a thermos with sand and pour liquid nitrogen into it. Read the potential across the thermocouple. When the cylinder is completely cooled and the temperature drops to about 70 K you can turn the power supply on. Adjust the power supply so the ammeter will read 0.1 A. It is a special power supply designed to keep the current steady. When the resistance of the superconductor changes with decreasing/increasing temperature, the voltage output will change appropriately to keep the current constant. Read the potential difference on the voltmeter. Use the 200 mV scale. At 70 K, there should be no potential difference between the voltage probes.

2. Let nitrogen evaporate slowly from the thermos. Read the temperature and observe the potential across the superconductor. You should record about 20 voltages in the temperature range between 80 and 120 K and an additional 20 points between 120 and 200 K. From time to time check the ammeter readings. If necessary, adjust the current to keep it constant.

3. The ratio of the voltage to the current flowing through the sample is the resistance of the superconductor between the two voltage probes. Since you kept the current constant, to get the resistance you will divide the voltages by the same number. If this resistance is plotted versus the thermocouple reading, the result should be similar to that shown in Fig. 8.2. Present your resistance measurements in the form of a graph and determine the critical temperature, at which the resistance gradually decreases to zero. Assess the error. Note, that the 1-2-3 and 2-1-2-2 superconductors have different critical temperatures, 92 K and 110 K, respectively. Identify your superconductor.

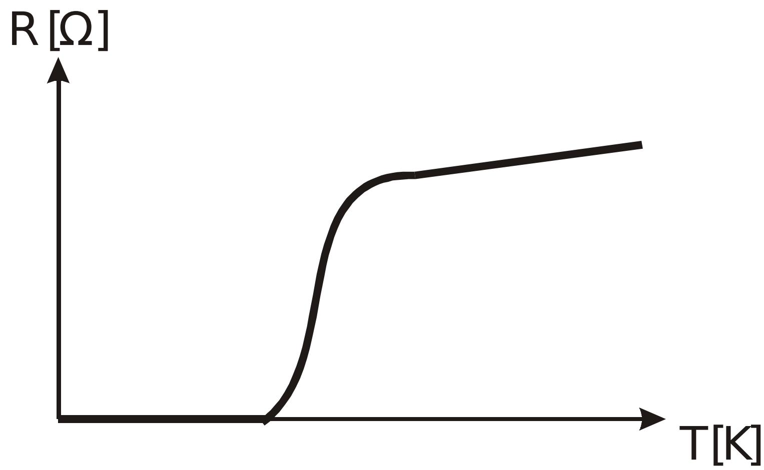

Figure 8.2: **Temperature dependence of resistance of a superconductor.**

8.3 Report

In your report answer the following questions:

1. Why did the liquid nitrogen boil when you poured it into the thermos?

2. When the nitrogen evaporates the cylinder becomes covered with a layer of white frost. This is a mixture of dry ice (solid CO_2) and regular ice (H_2O). Explain why CO_2 and H_2O condense on the cylinder.

3. A two probe method of measuring the resistance of the superconductor below the critical temperature shows a non-zero value. Why?

4. Explain the difference between a superconductor, a semiconductor, and a resistor.

Lab 9

Interference and Diffraction of Light

9.1 Introduction

9.1.1 Double Slit

Around 1800, the English scientist Thomas Young designed and performed an experiment that produced seemingly unexplainable phenomena. The outline of his experimental setup is shown in Fig. 9.1. Young observed the image of light passing first through one slit, S_0, and then two slits, S_1 and S_2 closely spaced and parallel to one another. He used filtered light from mercury lamp to ensure that he had a monochromatic light, of one wavelength. The first slit produced light of a definite phase relationship among various points on the wavefront, i.e. the light was coherent. The image that Young observed was a series of bright and dark areas on the screen (fringes) which did not represent a plain geometrical image of the double slit. A corpuscular theory, which assumes that light is a series of particles, could not explain this observation. This experiment indicated that light has to be treated as waves with all the consequences related to the wave motion, like diffraction and interference.

To calculate the positions of maxima and minima of intensities on the screen C let us consider point P, see Fig. 9.2. The waves arriving at point P travel distance S_1P and S_2P; hence the path difference between the two is (S_1P) - (S_2P). From Fig. 9.2 it is seen that this difference, is equal to (S_2Q). Since D is much larger than d (D is on the order of meters and d is measured in millimeters), and the angle S_1QS_2 is 90° so that the path difference is

$$(S_1P) - (S_2P) = (S_2Q) = d\sin\theta. \tag{9.1}$$

For P to be a bright fringe, the path difference must be an integral number of wavelengths,

$$d\sin\theta_m = m\lambda, \quad \text{where } m = 0, 1, 2, 3\ldots \tag{9.2}$$

In between the bright fringes are the dark fringes whose centers are given by

$$d\sin\theta_m = \left(m + \frac{1}{2}\right)\lambda, \quad \text{where } m = 0, 1, 2, 3\ldots \tag{9.3}$$

From Fig. 9.2 note that

$$\tan\theta_m = \frac{y_m}{D}. \tag{9.4}$$

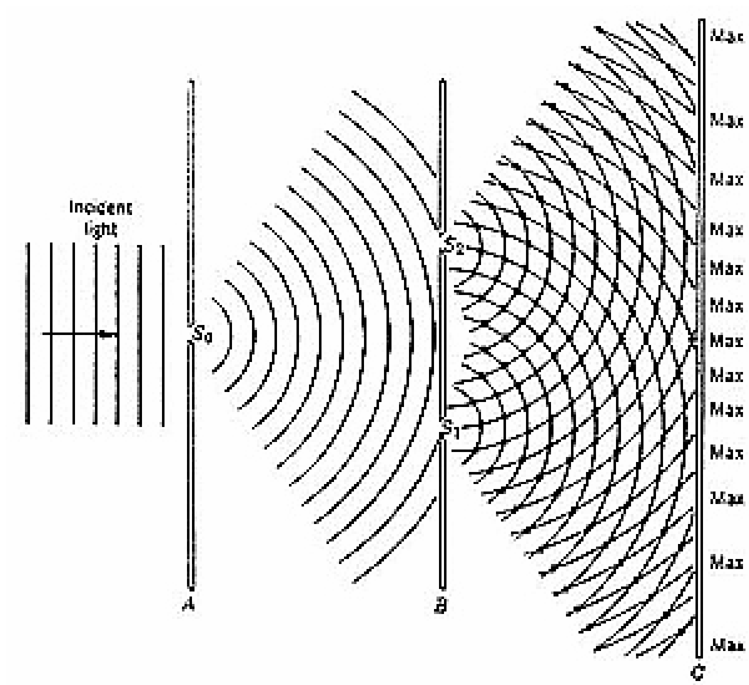

Figure 9.1: **Young's double slit experiment.** Light first passes through a narrow single slit creating a beam. It then hits a double slit causing an interference pattern on the screen.

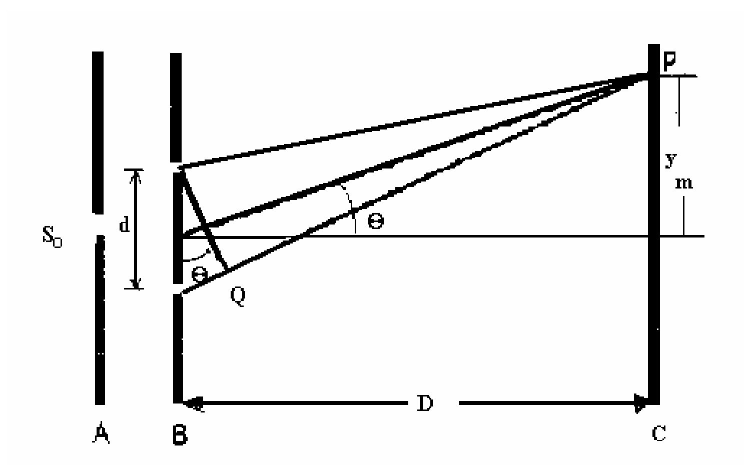

Figure 9.2: **Schematic of Young's experiment.** Light emanating from the two slits travels a different path length to reach the screen.

Since $y_m \ll D$ and $\sin\theta_m \equiv \tan\theta_m$, y_m/D may be substituted for $\sin\theta_m$. Thus, the conditions for maxima and minima, Eqs. (9.2) and (9.3), may be rewritten as

$$\frac{dy_m}{D} = m\lambda, \quad \text{where } m = 0, 1, 2, 3\ldots \quad \text{for maxima} \tag{9.5}$$

$$\frac{dy_m}{D} = \left(m + \frac{1}{2}\right)\lambda, \quad \text{where } m = 0, 1, 2, 3\ldots \quad \text{for minima.} \tag{9.6}$$

The first minimum is located at y_1 such that $dy_1/D = 12\lambda$. Thus λ can be found from the separation y between the first minima on both sides of the central peak

$$\lambda = \frac{yd}{D}. \tag{9.7}$$

In the introductory part of your report show that the intensity of the fringes varies as $\cos^2\theta$.

9.1.2 Single slit

Consider a single slit of width w as shown in Fig. 9.3. The plane wave fronts are incident from the left of the slit. Since each point on the incident wave front is a source of secondary waves, after passing through the slit, the new wave front is given by (AC) of Fig. 9.3. In order to calculate the conditions of maxima and minima of light intensity on the screen, consider the secondary waves from the top edge A and the center of the slit of width w. When these two waves reach the screen, their path difference will be (EF). From Fig. 9.3 it is seen that (EF) is related to the slit width as

$$(EF) = \frac{w}{2}\sin\alpha. \tag{9.8}$$

The minimum intensity is observed when the phase difference between the two waves is 12λ. From Eq. 9.8 we find that the general condition for destructive interference is

$$w\sin\alpha = n\lambda \quad \text{where } n = \pm l, \pm 2, \pm 3\ldots \tag{9.9}$$

Note that the minima for the diffraction pattern obey a similar criterion to that for the maxima for the double slit interference pattern. When the distance between the slit and the screen is much larger than the size of the slit, the distance between two minima on the screen, y, can be approximated by

$$y = \frac{D\lambda}{w}. \tag{9.10}$$

9.2 Procedure

It is much easier to repeat Youngs experiment using a laser than using a mercury lamp, therefore, in this experiment you will use a He-Ne laser. The goal of this experiment is to measure the wavelength of the laser light. The expected value is 632.8 nm.

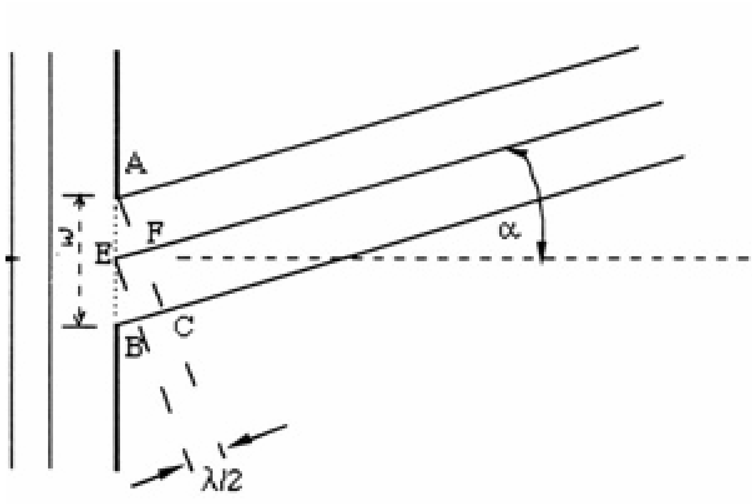

Figure 9.3: **The single slit experiment.** Light emanating from a single slit also creates an interference pattern.

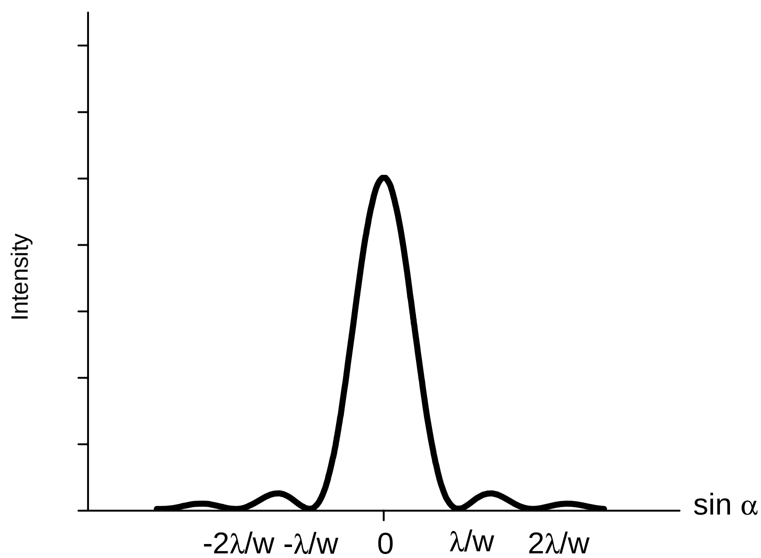

Figure 9.4: **Single slit diffraction pattern.**

1. Position the laser on the optical bench and align the beam. The beam should pass through the center of a rectangular opening in the aluminum plate attached to the linear translator with the fibre optic probe. First you will measure the diffraction pattern of a single slit. Attach the single slit to the magnetic stand and position it near the laser. Observe the diffraction pattern on a piece of white paper. The pattern consists of a central bright region flanked by much weaker maxima, see Fig. 9.4.

2. Move the optical bench until the diffraction pattern uniformly illuminates the opening in the aluminum plate. The diffraction pattern must be parallel to the opening and you may have to adjust bolts on the optical bench. Note that the translator should be perpendicular to direction of the laser light. Attach the fibre optic to the linear translator. Do not bend the fibre it is made of glass! The fibre should be close to the opening, but it must not touch the aluminum plate. Turn the motor on and stop it when the fibre is near the center of the opening. Attach the other end of the fibre to a photometer. Turn the photometer on and adjusts its range to measure the laser light.

3. Use a phone plug to connect the photometer with port A on the LabView interface box. In the next step you will prepare the computer to read and save the data, ie., laser intensity. Turn the computer on and login. On the desktop you will find icon Shortcut to Lab18. Double click on it. This is the shortcut that will open the LabView program. **Do not modify the LabView program. If you accidentally modified the program do not save the changes**. You may see windows asking you to register the software, or warn you that you are not a registered user, in each case enter OK. Finally a window similar to that shown in Fig. 9.5 will open. The diagram of the LabView program is shown in Fig. 9.6. You need to write the filename in the appropriate place, in the top left corner of the screen (see Fig. 9.5). I suggest that you use your name as a filename. If you add the extension `*.xls` to that filename it will be easy to open using Excel.

4. Before you start the experiment turn the motor on and move the carrier, with the fibre attached, to the end of the slide. The motor will automatically turn off when the carrier activates the end switch. To start recording light intensity click on the arrow in the top left corner of the LabView screen. Simultaneously turn the motor on. The fibre will move slowly across the opening in the aluminum plate and the photometer will record light intensity as a function of fibre position. The results, diffracted light intensity, will be displayed on the screen. The x-axis is the horizontal distance in arbitrary units. When the translator touches the end-switch at the other end of the slide you may stop the experiment by pressing the stop button on the screen, or wait until the system automatically stops after collecting 400 data points.

5. Open Excel and open the file you just saved. The data were saved in a folder DataLab 18 on the desktop. You may have to use Text Import Wizard if the file name does not have the `.xls` extension. Plot intensity (second column) vs. position (first column) and print the graph. Note two strong peaks at both ends of the graph — these are signals from the neon lamps. The lamps are exactly 9.5 inches apart. Use this information to convert arbitrary units to meters. Assume that the fibre travels with a constant speed and the data are recorded at the same time interval. Measure the distance between the minima and calculate the wavelength from Eq. (9.10). To use Eq. 9.10 you need to measure the distance between the fibre and the

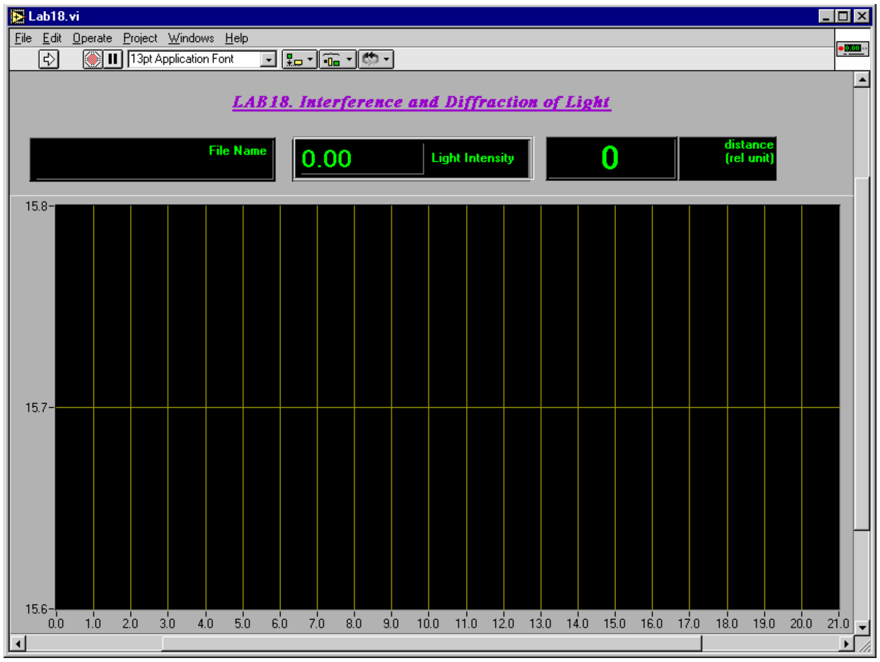

Figure 9.5: **Screenshot of the LabView program.**

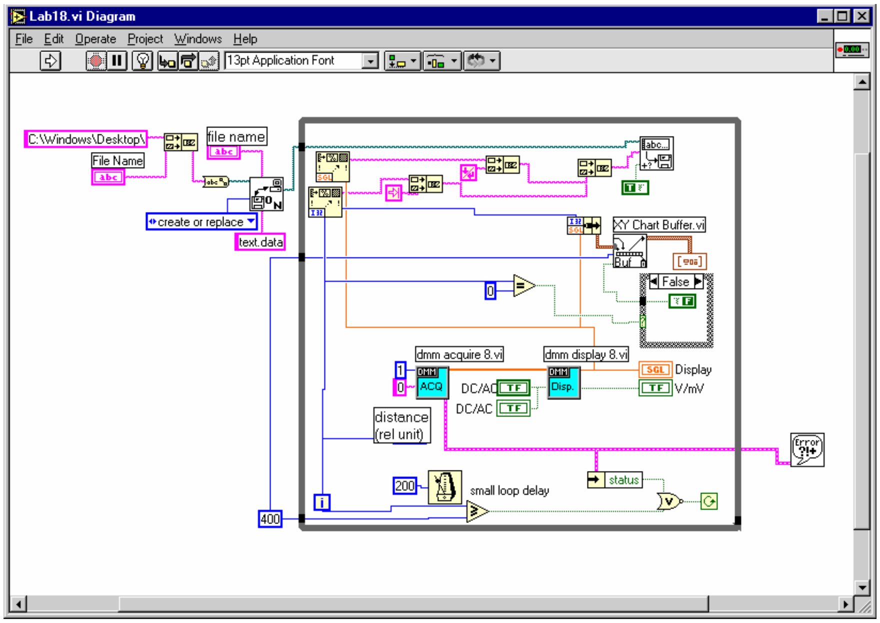

Figure 9.6: **Program diagram.** Light emanating from a single slit also creates an interference pattern.

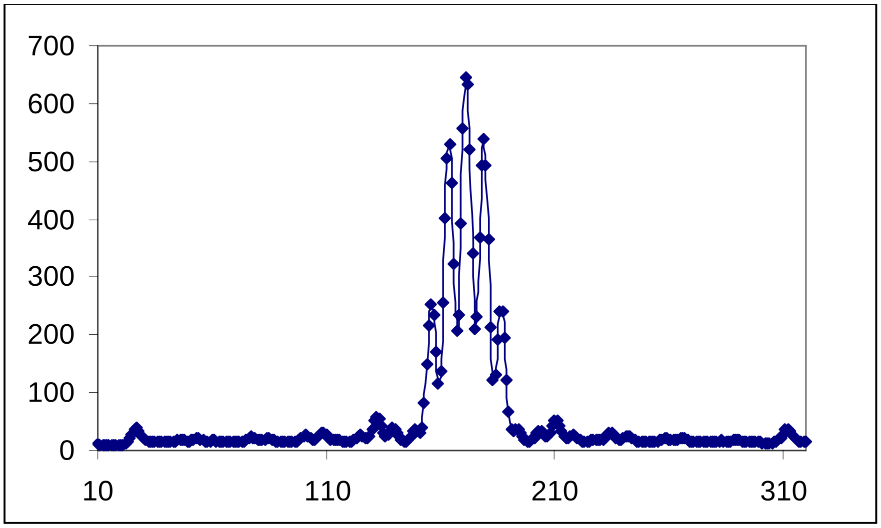

Figure 9.7: **Double slit interference.** A double slit interference pattern for the distance between the slits three times the slit width.

slit. The width of the slit can be found on the magnetic holder. Repeat the experiment for two other slits.

9.2.1 Double slit

1. Replace the single slit with a double slit and observe the pattern on the screen. You may have to move the laser away from the translator. Repeat the procedure described above for the single slit and record the interference pattern on the computer. It should be similar to that shown in Fig. 9.7. This pattern looks like that created by a single slit diffraction modulated by an interference pattern, and the total intensity can be approximated by a function

$$I = I_0 \left[\frac{\sin\left(\frac{\pi w}{\lambda} \sin\alpha\right)}{\frac{\pi w}{\lambda} \sin\alpha} \right]^2 \cos^2\left(\frac{\pi y d}{\lambda D}\right). \tag{9.11}$$

   You can find the wavelength of the laser beam by fitting intensity data to this function. This is a difficult task and instead we will use a simplified technique.

2. Measure the distance between the two minima on both sides of the central broad region and use Eq. 9.10 to find λ. Measure the distance y between the sharp minima of fine structure inside the broad central region and use Eq. 9.7 to find λ. Values of w and d can be found on the slit's mount. Repeat for two more double slits of different widths and slit separations. Use different distances between the slits and the screen.

9.3 Report

In the introduction show that the intensity of the double-slit interference pattern changes as

$$I = I_0 \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right), \tag{9.12}$$

or for large distances D,

$$I = I_0 \cos^2\left(\frac{\pi y d}{\lambda D}\right). \tag{9.13}$$

In the report include graphs of light intensities after it passes through 3 single slits and 3 double slits. Record calculated wavelengths in the tables below, note that you will use three different measurements to find λ.

Single slit measurements.

Slit width (mm)	Calculated λ (nm)

Double slit measurements.

Slit width (mm)	Separation between slits (mm)	Wavelength (nm) from Eq. (9.10)	Wavelength (nm) from Eq. (9.7)

Lab 10

Light Emitting Diodes

10.1 Introduction

The goal of this experiment is to relate the observed properties of the compound semiconductors, such as the wavelength of emitted light and the excitation voltage to their composition. You will use four different light emitting diodes (LEDs), which are solid-solution semiconductors $GaAs_{1-x}P_x$.

Compared with conductors, semiconductors have fewer charge carriers, higher resistance, and the temperature coefficient of resistivity is both large and negative. The resistivity of a pure semiconductor is so high that it can be treated as an isolator. The electrical properties of metallic conductors and semiconductors are so different that to explain them we must use the quantum model of conductivity. In a metallic conductor the valence band is partially filled, see Fig. 10.1. When an electric field is applied, energy of the valence electrons is increased and as a result current flows. In an isolator the valence band is completely filled and the gap between the conduction band is large. If an electric field is applied no current can occur because the electrons cannot increase their energy. The energy gap is too great for the electrons to jump to a higher energy level. In a semiconductor, the energy gap between the valence and conduction band is small and thermal excitation can cause the electrons to jump to the conduction band. The number of carriers increases rapidly with temperature resulting in decreased resistivity. Impurities can add conduction charges. Addition of impurities, called doping, is the mechanism used by manufacturers to control the properties of semiconductor devises. Elements from column III and V, or II and IV can be combined to form compounds of various energy gaps.

When energy is supplied to a semiconductor (it may be in the form of heat, electric field, or radiation) an electron is removed from the valence band generating there a vacancy, and transferred to the conduction band. The vacancy created in the ground state is called a 'hole'. When an excited electron returns to the valence band, the energy is released, sometimes in the form of light. This process is called the electron-hole recombination. The law of conservation of energy requires that the light emitted has the energy equal the width of the gap. Compounds of larger energy gaps will emit light of larger energy and shorter wavelength. Therefore, is customary to measure the width of the energy gap in units of wavelength [μm] or energy [$1\ \text{eV} = 1.6 \times 10^{-19}$ J].

The strength by which an electron is held in a bond depends among others on the distance between the atoms. The lattice constant in pure GaP is smaller than in pure GaAs. When phosphorus is added into the GaAs solid solution, the symmetry of the lattice remains the same but the lattice constant increases. The lattice constants of LEDs fabricated in the $GaAs_{1-x}P_x$

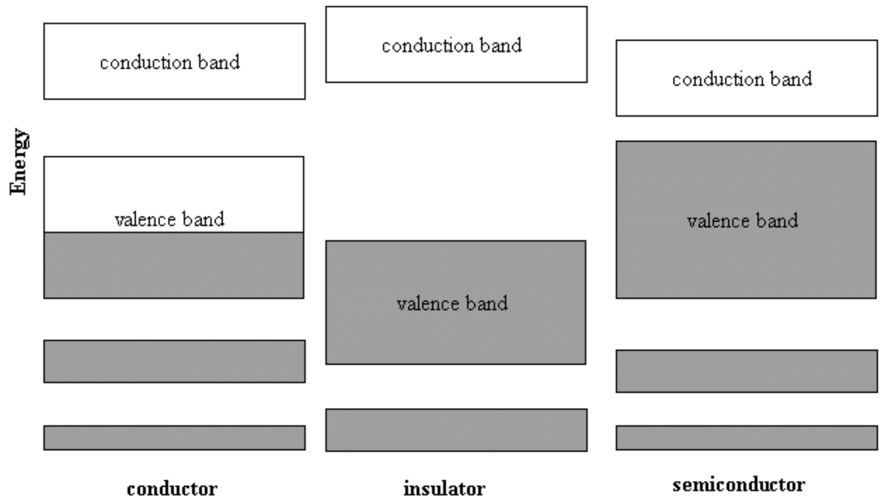

Figure 10.1: **Allowed energy levels for the electrons in a solid state.** The pattern of allowed bands and forbidden gaps is shown for a conductor, an insulator and a semiconductor.

system lie along the connecting points for pure GaAs and pure GaP, see Fig. 10.2. It is seen that shorter lattice constants result in larger energy gap. One can tune the color emitted by the LED by changing the concentration of phosphorus in the compound.

When a voltage applied across the LED is continuously increased, initially nothing will happen because the energy of the electric filed is not sufficient to excite electrons from the ground state. Remember that voltage is proportional to energy. When the energy is increased above the band gap energy, current can begin to flow and light may be emitted. Measurement of the voltage for the minimum current provides an estimate of the band gap energy. Another estimate of the band gap energy is the measurement of the wavelength of the emitted light.

10.2 Procedure

In this experiment you will use five LEDs of the following compositions: $GaAs_{0.40}P_{0.60}$, $GaAs_{0.35}P_{0.65}$, $GaAs_{0.15}P_{0.85}$, $GaAs_{0.00}P_{1.00}$, and InGaN. Galium nitride diode doped with indium emits blue light and has different properties then the other diodes. The LEDs all look identical so do not mix them up. Two sets of circuits have been prepared; their schematics are shown in Fig. 10.3. The circuits containing large resistors are been marked: "1 M", those with small resistors "1 kΩ". The circuits are turned on by attaching a 9 V battery to the battery snap. You will conduct two different measurements.

10.2.1 Measurement of the band-gap potential and composition of the LEDs

In the first series of experiments you will measure the voltage corresponding to a minimum current flow. We prepared circuits with a constant voltage, 9 V, and a 1 MΩ resistor to limit the current. The magnitude of the currents in a circuits is measured in microamperes and thus we may assume that those are the minimum currents.

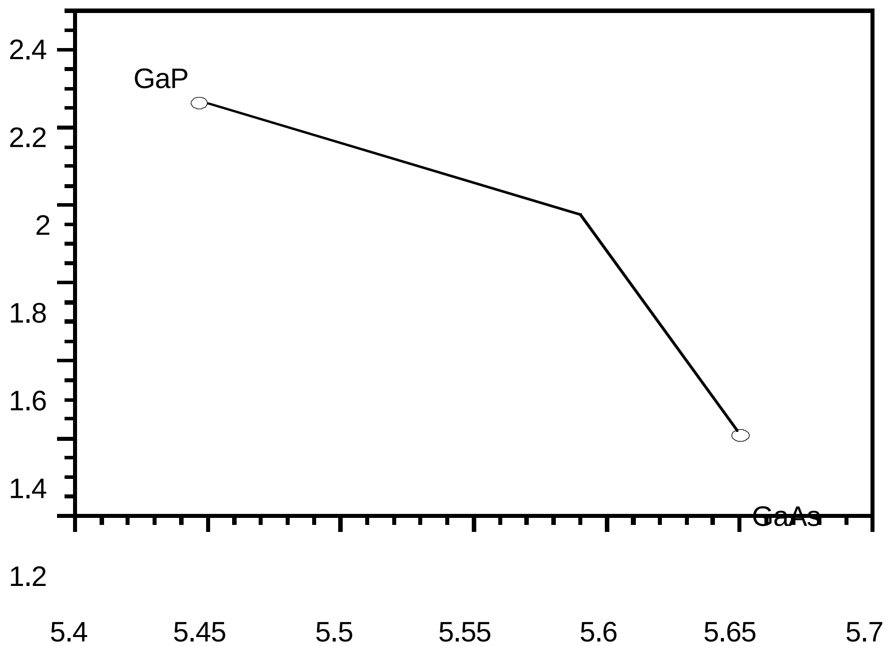

Figure 10.2: **Energy gap of the $GaAs_{1-x}P_x$ compounds as a function of the lattice constant.** The concentration of phosphorus, x, varies between 0 and 1.

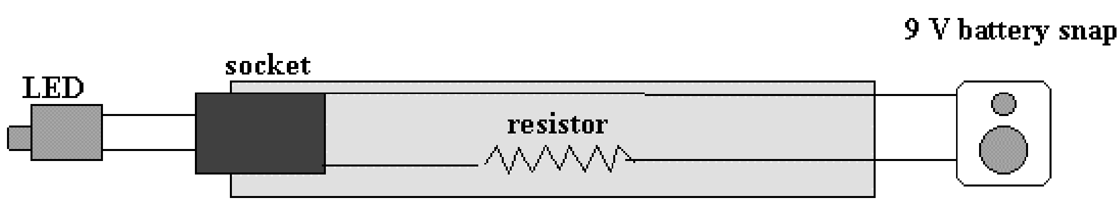

Figure 10.3: **Circuit for the LED socket.** Two sets of sockets are used with resistance of the resistor equal 1 kΩ or 1 MΩ .

Table 10.1: Relationship between colour, wavelength and energy of light

Colour of light	Approximate wavelength (nm)	Approximate energy (eV)
Ultraviolet	400	3.10
Violet	410	3.00
Violet-blue	430	2.90
Blue	480	2.60
Blue-green	500	2.50
Green	530	2.30
Green-yellow	560	2.20
Yellow	580	2.10
Orange	610	2.00
Red	680	1.80
Red-purple	720	1.70

1. Attach the snap-on-clips to the LED wires and measure the DC voltage on a voltmeter. Record that value. You may be able to see the emitted light if the lights in the room are turned off.

2. Immerse the LED into liquid nitrogen, wait about 30 seconds for the temperature to drop to 77 K, and measure V_{LED}, the voltage across the LED. **CAUTION: Liquid nitrogen is extremely cold. Do not allow it to come to a contact with your skin or cloth.**

3. Repeat for all five LEDs and record in the table below. In the report, identify the composition of the LEDs. Analyze Fig. 10.2 and explain the temperature induced changes in the voltage corresponding to the minimum current flow.

Potentials across the LED.

Colour of light emitted by LED	V_{LED} at room temperature	V_{LED} at 77 K

10.2.2 Measurement of the wavelength and compositions of LEDs

1. Connect the socket with the LED with 1 kΩ resistor to the 9 V battery. The current is relatively large and you should be able to identify the colors of emitted light. Use Table 10.1 to approximate the band gap energy.

2. In the next step you will measure the wavelength of light using USB4000 spectrometer. The spectrometer measures the amount of light of each wavelength in the sampled spectrum. It consists of a slit, diffraction grating, mirrors, lenses, and a 2048-element linear CCD-array detector. All those elements are mounted on a single plug-in computer card. The light

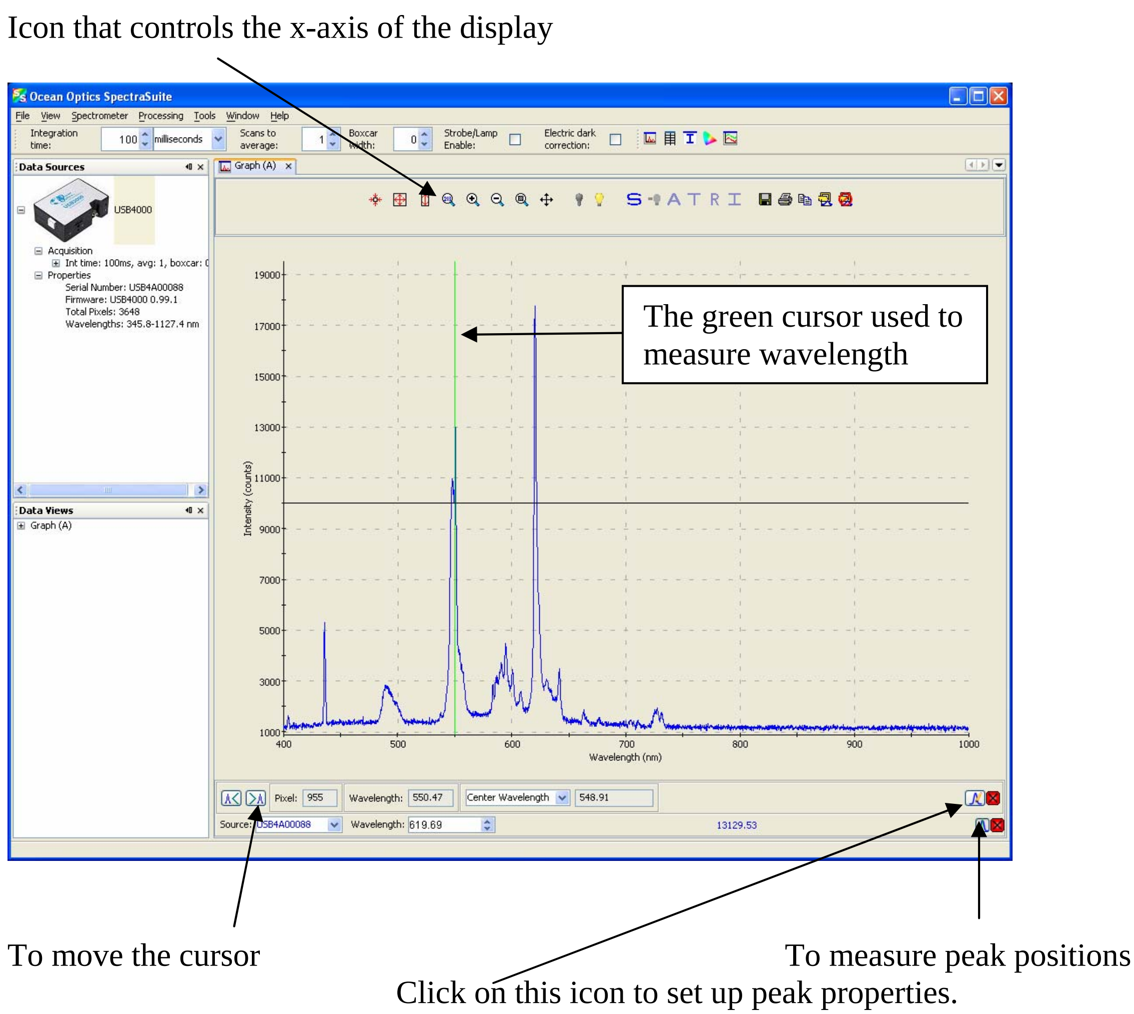

Figure 10.4: **SpectraSuite.**

emitted by a sample is collected and sent to the spectrometer via a fibre. The USB4000 is a new generation spectrometer of a very small size. But despite its small dimensions it has a remarkable spectral resolution of 1.5 nm and very high sensitivity. It is so sensitive that we will not use a focusing lens to collect the light onto the 400 μm diameter single strand optical fiber. The operating software, SpectraSuite by OceanOptics, controls the data acquisition, provides real-time interface to a variety of spectral processing functions, and displays the results. That software has been installed and configured, and the computer should be ready to start the experiment. Find the SpectraSuite icon and double click on it. A new screen with a toolbar and pull down menu will appear, similar to that shown in Fig. 10.4.

3. The program automatically starts recording spectra. You may adjust the integration time to get a better signal to noise ratio. To stop data acquisition, go to Spectrometer, Acquisition and then select Stop. To resume data acquisition select Resume. To adjust the wavelength and intensity range click on the icon that looks like a magnifying glass with numbers 213

inside. Type new range for the wavelengths (400 to 900 is the recommended range) and intensities. When you are satisfied with the quality of the spectrum you may find peak positions. Right click on the spectrum and a green cursor will appear. Simultaneously, below the graph an additional toolbar will appear.

4. Click on the spectrum icon which you may find in the right bottom corner of the window and the threshold line (a horizontal solid line) will appear along with a new window that will allow you to control selection of the peaks. The minimum peak width should be at least 5 pixels and could be as high as 200. Write an appropriate value for the baseline so that only few peaks will actually be measured. You do not want to record all small peaks, most of which are most likely due to noise fluctuations.

5. Use the buttons to move the cursor to the next peak (left or right). Record the wavelengths of the peaks which will be listed in the box Center Wavelength. To print click on the printer icon and you will see a window similar to that: Select the Processed spectrum and Zoomed Area. You may add comments in the left bottom box; for example, list measured wavelengths of peaks. Select Print and follow further instructions. To print you may have to go to the card reader near the system printer to start the process.

6. To record several spectra on the same page go to File, New, and select Spectrum Graph. A new spectrum will appear. It will have a different colour. To stop data acquisition you may have to click on the new spectrum and then go to Spectrometer and Data Acquisition. Repeat the procedure as many times as needed. To read wavelengths repeat the procedure outlined above and select the proper spectrum from the box source at the left bottom corner of the graph by pulling down the name of the spectrometer. When you select the spectrum the colour of the spectrometer name will change.

7. Hold the red light emitting LED close to the fibre, which is attached to a stand with a foam cup. Observe the spectrum and if it varies widely you may need to hold the LED more steadily. Adjust the integration time so that the maximum intensity is roughly 3000 counts. Adjust the y-axis and select the spectral region so it displays only the significant part of the spectrum, for example, for the red LED the spectral region could be 550 nm to 750 nm. Use the cursor to find the wavelength of the peak maximum and record that value. If you are satisfied, send the spectrum to the printer.

8. Pour liquid nitrogen into the foam cup. Immerse the red LED in liquid nitrogen and hold it for 10 to 20 seconds. Does the color change? Remove the LED from liquid nitrogen and when it is still cold record the spectrum following the steps above. If you hold the LED in the air for too long, the temperature will increase, and you may have to repeat the procedure. Record the wavelength of the maximum of the band. Print the spectrum in the same spectral range as for the measurements at room temperature. Let the LED warm back to room temperature and record the spectrum, but this time, do not print it. Are spectral changes reversible? **DIP IN LIQUID NITROGEN ONLY THE HEAD OF THE LED; DO NOT DIP THE CIRCUIT AND PLASTIC HOLDER. CAUTION: Liquid nitrogen is extremely cold. Do not allow it to come to a contact with your skin or cloth.**

9. Repeat for the remaining LEDs, but do not print the spectra. Instead, record the wavelengths of the maxima in the table below. The blue light emitting LED does not emit light at 77 K.

For some LEDs you will observe band splitting and multiple peaks. Interpretation of this effect is not simple and is related to added impurities, other than phosphorus. Manufacturers do it to enhance the light intensity. For those LEDs the temperature induced shift may be discussed in terms of the shift of the "center of the band" and not of the band maximum.

Wavelengths of the emitted light.

LED	Wavelength of maximum at 300 K (nm)	Wavelength of maximum at 77 K (nm)
Red		
Orange		
Yellow		
Green		
Blue		

10.3 Report

In the report explain the negative value of the thermal coefficient of resistivity for semiconductors. Identify the composition of the LEDs, i.e., explain the observed temperature induced band gap energy changes and wavelength shifts.

Lab 11

Reflection and Refraction

11.1 Introduction

11.1.1 Reflection

When light strikes the surface of a material, some of the light is reflected. The reflection of light rays from a plane surface like a glass plate or a plane mirror is described by the law of reflection: "The angle of reflection is equal to the angle of incidence", or

$$\theta_i = \theta_r. \tag{11.1}$$

These angles are measured from a line perpendicular or normal to the reflecting surface at the point of incidence, Fig. 11.1 (left).

11.1.2 Refraction

When light passes from one medium into an optically different medium at an angle other than normal to the surface, it is "bent" or undergoes a change in direction, as show in Fig. 11.1 (right). This is due to the different velocities of light in the different media. For θ_1, the angle of incidence, and θ_2, the angle of refraction, we have

$$\begin{aligned} \sin\theta_1 &= \frac{v_1 t}{d} \qquad (11.2) \\ \sin\theta_2 &= \frac{v_2 t}{d} \end{aligned}$$

or

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1 t}{v_2 t} = n_{12}, \tag{11.3}$$

where the ratio of velocities is called the relative index of refraction. For light travelling initially in a vacuum, the relative index of refraction is called the absolute index of refraction or simply the index of refraction, and

$$n = \frac{c}{v}, \tag{11.4}$$

where c is speed of light in a vacuum and v the speed of light in the medium. Snell's Law can then be written

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{11.5}$$

where n_1 and n_2 are the indices of refraction of medium 1 and 2, respectively.

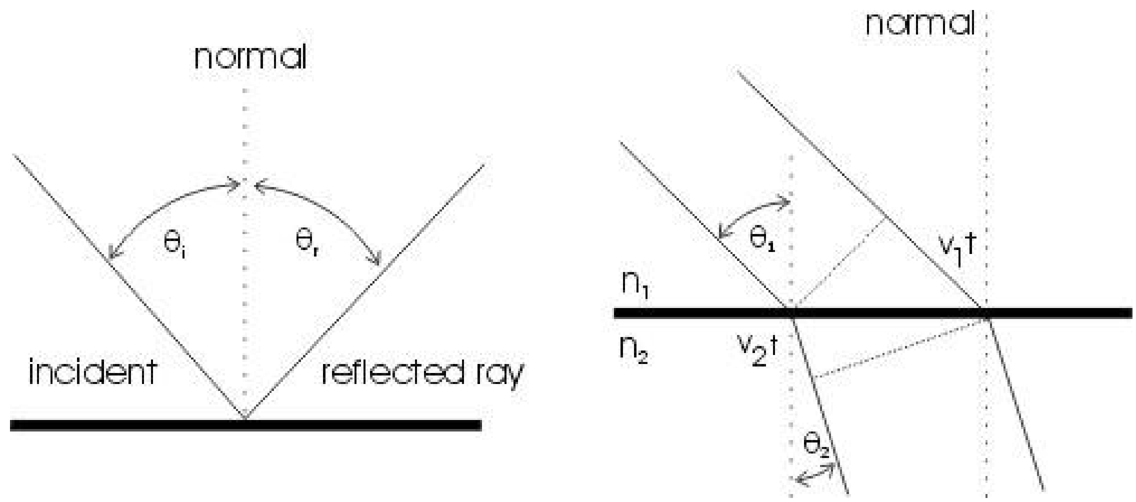

Figure 11.1: **Reflection and refraction.** When light strikes a material, some of the light is reflected (left) and some is refracted (right).

11.2 Procedure

You will do three different experiments, listed below as A, B, and C. You may use a photometer and the fibre optic probe (recommended) or use your eye to detect maximum intensity of light. The laser or an incandescent light source can also be used in all three methods. When the laser is used no aperture mask is then needed. If you decide to use the laser, do not look into the beam. Observe reflected and transmitted light using a piece of paper. Detect the position of the laser beam using a light detector and fibre optics.

11.2.1 Angles of Incidence and Reflection

1. Position the incandescent light source on the left end of the optical bench, and place the angular translator about 25 cm from the end of the light source housing (or the laser). Make sure the 0° and 180° marks lie on a line parallel to the bench. Finally adjust the rotating table so that the scored lines run perpendicular and parallel to the bench.

2. Attach the aperture mask to the standard component carrier and place it between the light source and angular translator so that the mask is d centimeters from the center of the translator. The distance d (about 6.5 cm) is the measured distance from the center of the angular translator to the first analyzer holder on the movable arm (See Fig. 11.2).

3. Center the viewing screen on the special component carrier (a shorter magnetic holder) designed for use with the angular translator. Place the assembly on the rotating table of the translator so that the front surface of the viewing screen coincides with the scored line on the table, which runs perpendicular to the optical bench.

4. Now switch on the light and adjust the aperture mask's position (don't move the component carrier), until the entire image is on the viewing screen. With the aid of the millimeter scale marked on the screen, center the image horizontally.

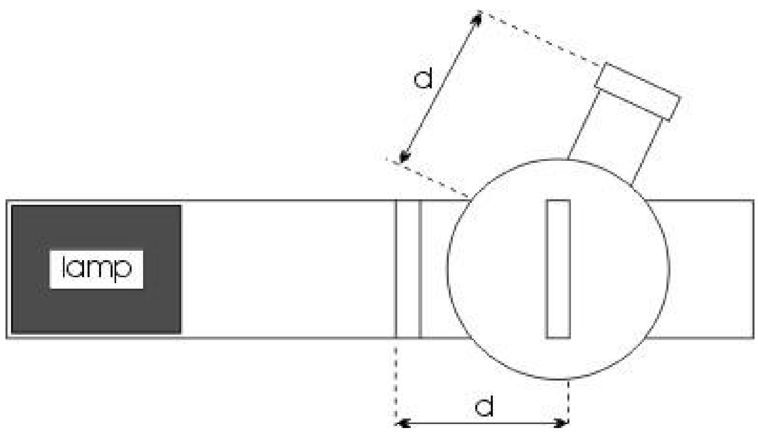

Figure 11.2: **Experimental setup.** The aperture mask should be placed between the light source and angular translator so that the mask and holder are equidistant from the special component carrier.

5. Now replace the viewing screen with the flat surface mirror such that the mirror surface coincides with the perpendicularly scored line.

6. Rotate the table a set number of degrees (for example, 30°), and then move the arm until the reflected image is centered on the aperture of the viewing arm. Record the angle which the arm makes with the mirror. Repeat for 10 various settings of the rotating table. What is the relation between the angle of incidence and the angle of reflection? (Angle of incidence is the angle the incident ray makes with the normal to the reflecting surface; similarly for the angle of reflection.)

11.2.2 Index of Refraction: Part I

1. Take a square piece of paper about 5 centimeters on a side with a millimeter scale across the middle.

2. Using the same equipment set-up as in Experiment 1, put the paper between the glass plate and the special component carrier on the angular translator. The magnetic surface will hold the glass plate and paper in place. The millimeter scale should run horizontally.

3. Adjust the position of the special component carrier until the back surface of the glass plate coincides with the perpendicularly scored line on the table.

4. With the glass plate sitting perpendicular to the bench, adjust the position of the aperture mask so that one vertical edge of the image on the paper lines up with the scored line on the table which is parallel to the bench. If the glass does not alter the lights' path, the vertical edge which was centered should remain centered although the translator's table is rotated. When you use the laser observe the position of the center of the beam.

5. Rotate the table and record what happens to the previously centered beam. Is the incident ray refracted toward or away from the normal to the glass? Figure 11.3 shows how to calculate

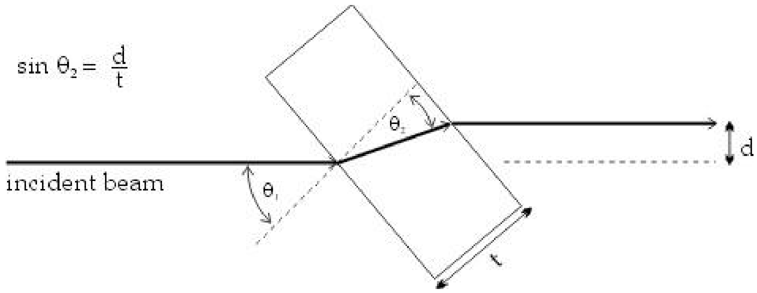

Figure 11.3: **Refraction by a plate.** The incident beam is refracted through the glass plate. Note that $\sin\theta_2 \approx d/t$.

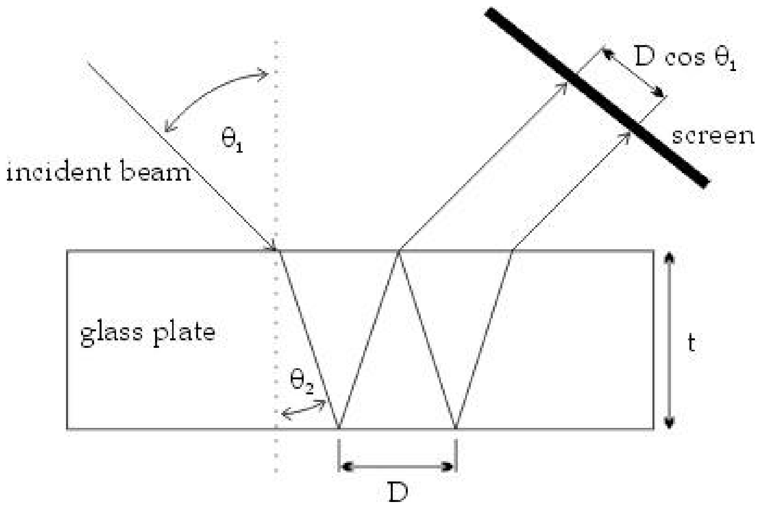

Figure 11.4: **Secondary reflections.**

the index of refraction given the angle of rotation and the edge displacement of the image. Using this method, a large error is introduced since the triangle formed by the refracted beam, glass surface and the normal is not a right triangle. Since the measured value of θ_2 is not accurate the index of refraction calculated from $n = \sin\theta_1/\sin\theta_2$ can be treated at best as a first approximation. The method described below gives more accurate results.

6. Replace the glass plate with the acrylic plate and determine the index of refraction for acrylic.

11.2.3 Index of Refraction: Part II

1. With the glass plate perpendicular to the bench and the paper with the millimeter scale on it, put the screen on the viewing arm. Rotate the table to a convenient angle. Light is refracted toward the normal when passing from air to glass. Is the same true when light propagates from glass to air? By observing the positions of the image on the viewing screen, you can see that the refraction must be away from the normal at a glass-air interface. (See Fig. 11.4).

2. There should be at least two reflected images from the plate. Measure the distance between them (i.e. between their centers). You can measure the distance between the two images observed on the back of the plate using the paper with the millimeter scale or in the front of the plate on the screen placed on the viewing arm. Then if D is the distance separating them, t is the plate thickness, θ_1 is angle of incidence, and θ_2 is angle of refraction, we have

$$\tan\theta_2 = \frac{D}{2t}. \tag{11.6}$$

   Calculate θ_2 for various θ_1. Then calculate n from $n = \sin\theta_1/\sin\theta_2$.

3. Repeat both methods with the acrylic plate.

11.3 Report

ATTENTION: If you decide to use Excel remember that its trig functions work only in radians and angles measured in degrees must be converted first to radians.

Present the data in the form of a table. In the discussion answer all the questions asked in section 2. In the introduction discuss total internal reflection and its applications.

Lab 12

Spectrum of Hydrogen and Rydberg Constant

12.1 Introduction

The electrons in an incandescent light source undergo thermal excitation and emit electromagnetic radiation (light) of many different wavelengths, producing a continuous spectrum. However, when light emitted from excited gases or vapourized liquids, or solids is analyzed, line spectra are observed. Different substances have characteristic spectra — i.e. they have a characteristic set of lines at specific wavelengths. The characteristic colour of light from a gas discharge is indicative of the most intense spectral line or lines in the visible region. For example, light from a hydrogen discharge has a red glow due to an intense emission line with a wavelength of 656.1 nm.

The characteristic spacing of the spectral lines in the spectrum of hydrogen was observed by spectroscopists in the late 1800's. The wavelengths of the visible region of hydrogen, called the Balmer series, were found to fit the formula

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \quad n = 3, 4, 5 \ldots \tag{12.1}$$

where R is the Rydberg constant, with a value of 1.097×10^{-2} /nm. Later, other spectral series in UV and infrared were discovered and showed that they all can be expressed as

$$\frac{1}{\lambda} = R\left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right), \tag{12.2}$$

where n_i and n_f are integer numbers. This was an empirical expression and remained unexplained until a quantum model of the hydrogen atom was offered.

The hydrogen spectrum is of particular theoretical interest because hydrogen, having one proton and one electron, is the simplest atom. Neils Bohr developed a quantum theory for the hydrogen atom which explains the spectral lines as resulting from electron transition between energy levels i and f (see Fig. 12.1). In this model the energy of an electron on the orbit n is quantized and expressed as

$$E_n = -\frac{2\pi^2 k^2 e^4 m}{h^2 n^2} = -\frac{13.6 \text{ eV}}{n^2} \quad n = 1, 2, 3, 4 \ldots \tag{12.3}$$

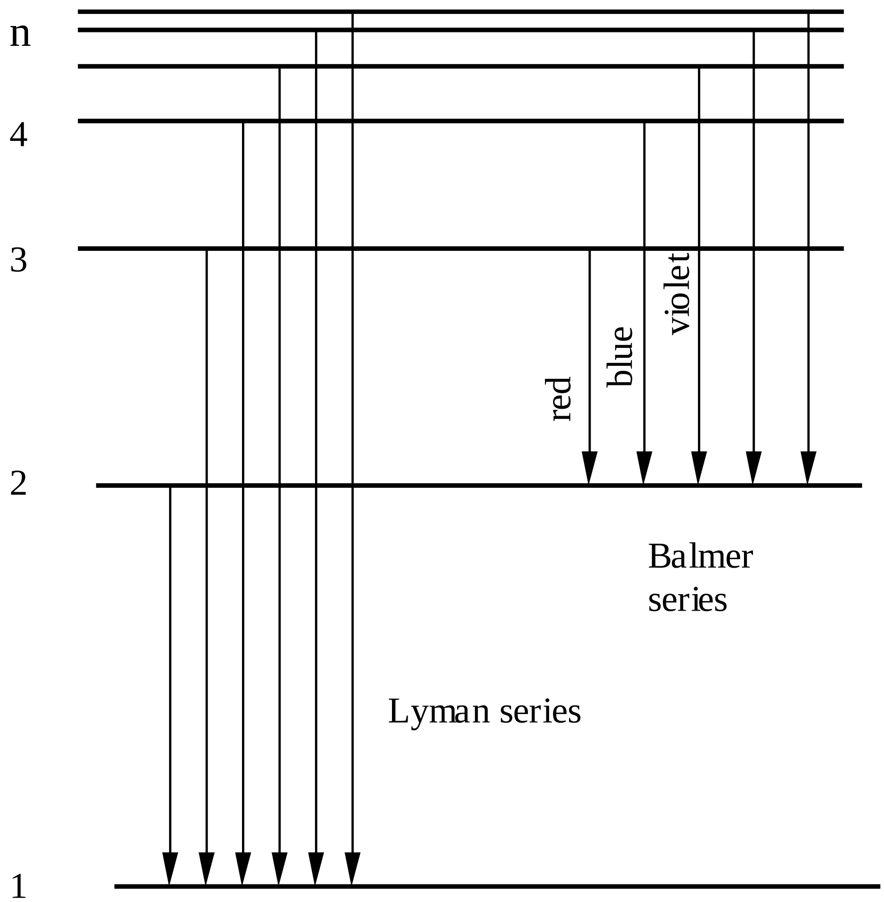

Figure 12.1: **Hydrogen energy level transitions.** Lyman and Balmer series of spectral lines for atomic hydrogen.

where m is the mass and e the charge of an electron, k is the Coulomb constant, and h is Plancks constant, $h = 6.63 \times 10^{-34}$ J $\cdot$ s $= 4.16 \times 10^{-15}$ eV $\cdot$ s. n is the quantum number assigned to the orbit. The wavelengths of the spectral lines can be calculated from Eq. (12.3).

If the electron jumps from one orbit, whose quantum number is n_i, to another orbit, whose quantum number is n_f, it emits a photon of frequency

$$f = \frac{E_i - E_f}{h}. \tag{12.4}$$

Often it is more convenient to describe this transition in terms of the wavelength of the emitted light. The wavelength can be calculated from Eqs. (12.3) and (12.4) and expressed as

$$\frac{1}{\lambda} = \frac{f}{c} = \frac{2\pi^2 m k^2 e^4}{ch^3} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right), \tag{12.5}$$

where c is the speed of light in vacuum, $c = 3 \times 10^8$ m/s. A comparison of this result with Eq.

(12.1) gives the following expression for Rydbergs constant

$$R = \frac{2\pi^2 m k^2 e^4}{ch^3} = \frac{13.6 \text{ eV}}{hc}. \tag{12.6}$$

When n_f equals 2 and $n_i = 3, 4, 5 \ldots$, we get the Balmer series,

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n_i^2}\right) = \frac{13.6 \text{ eV}}{hc}\left(\frac{1}{2^2} - \frac{1}{n_i^2}\right) \tag{12.7}$$

or

$$\lambda = \frac{hc}{13.6 \text{ eV}\left(\frac{1}{2^2} - \frac{1}{n_i^2}\right)}. \tag{12.8}$$

For another series of lines, the Lyman series, $n_f = 1$ and $n_i = 2, 3, 4, 5 \ldots$. The energy diagram for hydrogen is shown in Fig. 12.1. Vertical arrows indicate transitions between energy levels. During each transition a photon of frequency $f = (E_i - E_f)/h$ is emitted.

12.2 Procedure

You will measure the spectra using USB2000 or USB4000 spectrometers. The spectrometer measures the amount of light of each wavelength in the sampled spectrum. It consists of a slit, diffraction grating, mirrors, lenses, and a 2048 element linear CCD-array detector. All those elements are mounted on a single plug-in computer card. The light emitted by a sample is collected and sent to the spectrometer via a fiber. The USB2000 is a new generation spectrometer of a very small size. But despite its small dimensions it has a remarkable spectral resolution of 1.5 nm and very high sensitivity. It is so sensitive that we will not use a focusing lens to collect the light.

The operating software, Spectra Suite by OceanOptics, controls the data acquisition, provides real-time interface to a variety of spectral processing functions, and displays the results. That software has been installed and configured, and the computer should be ready to start the experiment.

File menu functions include: NEW (opens a new window and starts acquiring data from the spectrometer); OPEN (opens a dialogue box and allows to read data saved as binary file); CLOSE (closes the current graph window); SAVE SAMPLE SPECTRUM (opens a dialogue box that allows you to save the current spectrum); PRINT (spectrum with a title and grid is printed as seen on the screen); PRINT PREVIEW (allows to view the spectrum before it is printed); EXIT (ixits OOIBase). Functions STORE DARK SPECTRUM, STORE REFERENCE SPECTRUM, and EXPORT SPECTRUM will not be used in this experiment.

VIEW menu functions include: SCOPE MODE (this command switches the current window into the Scope Mode and graphs the signal in terms of counts), ABSORBANCE MODE, TRANSMISSION MODE, IRRADIANCE MODE (will not be used them in this experiment); SNAPHOT (freezes the data acquisition); AUTOSCALE Y AXIS (adjusts the vertical scale); CHANGE GRAPH SCALE (opens a dialogue box to allow you manually set the horizontal and vertical scales of the graph); UNSCALE GRAPH (returns the graph to the default scale); COLORS (selects colours for the frames, background, trace, etc); CURSOR (toggles the vertical cursor on the current graph. The cursor can be moved by yellow arrows in the toolbar or by the arrow keys on the keyboard); GRID (toggles the display of a vertical and horizontal grid on the graph). SETUP menu functions include: CONFIGURE HARDWARE (do not use); CONFIGURE SPECTROMETER (do not use); TIME SERIES ACQUISITION (we recommend the default values but you may select the number of scans, set the delay between the scans, and set the acquisition mode to scope); SUBTRACT DARK SPECTRUM (do not use); DATA ACQUISITION (select the normal mode, enable S2000 strobe and pick 1 to 5 samples for average); INTEGRATION TIME (select integration time so that the signal will reach approximately 3000 counts); DATA ANALYSIS (improves the signal to noise ratio by averaging spectra, you do not need to use it but if you want you may set the dynamic average to 5 and the boxcar width to 3); SET GRAPH TITLE (specify the title of the spectrum before printing).

From all those functions, you will probably need INTEGRATION TIME, SNAPSHOT, CURSOR, CHANGE GRAPH SCALE, SET GRAPH TITLE, PRINT, and maybe also SAVE SAMPLE SPECTRUM.

1. Find the Spectra Suite icon and double click on it. A new screen with a toolbar and pull down menu will appear.

2. Hold the fibre close to a mercury lamp. **BE CAREFUL — OPTICAL FIBRE IS MADE OUT OF GLASS AND CAN BE EASILY BROKEN. DO NOT BEND IT!** Observe the spectrum and if it varies widely you may need to hold the fibre more steadily. Adjust the integration time so that the maximum intensity is roughly 3000 counts. Use the SNAPSHOT function to freeze the display. Adjust the y-axis and select the spectral region so it displays only the significant part of the spectrum. If you are satisfied with the spectrum you may print it. You should observe several peaks located at about:

   - 436 nm — blue
   - 492 nm — aqua
   - 546 nm — green
   - 577 nm — yellow
   - 579 nm — yellow

3. With the power cord to the power supply disconnected, replace the mercury tube with the hydrogen tube and record the spectrum of hydrogen. Read the wavelengths of the lines.

4. Plot a graph of the reciprocal of wavelength l/λ versus $1/n^2$. Begin the abscissa scale with zero. Draw the best straight line that fits the data points and determine the slope of the line. Note that

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n_i^2}\right) = \frac{R}{4} - \frac{R}{n_i^2} \tag{12.9}$$

   has the form of a straight line, $y = mx+b$, with a negative slope equal to the Rydberg constant. Compare the slope of the line with the accepted value of the Rydberg constant. Also, compare the value of Planck's constant obtained from Eq. (12.6) with the value $h = 6.63 \times 10^{-34}$ J $\cdot$ s.

12.3 Report

In the report discuss:

1. the origin of other spectral series for atomic hydrogen (Lyman, Paschen, etc.).

2. how you make hydrogen atoms emit light? Hint — in order to see the emitted light, hydrogen atoms were first pumped into excited states of various quantum numbers n.

3. Atoms do not only emit light but also absorb it. Where do you expect to observe the absorption lines for hydrogen? Suggest an experiment setup to measure absorption spectra.

Lab 13

AC Circuits and Electrical Resonance

13.1 Introduction

Consider an AC circuit containing a resistor, an inductor, and a capacitor connected in series, as seen in Fig. 13.1 (left). Remember that the same current flows through all three elements. Since the current is common to all elements, we will take it as a reference, and will measure voltages across the resistor, the capacitor and the inductor with respect to the current. It is convenient to present the results in the form of a graph in which the horizontal axis represents the current, see Fig. 13.1 (right). The voltage across the resistor is given by Ohm's law

$$V_R = IR \tag{13.1}$$

and is in phase with the current. Thus, V_R is displayed on the x-axis. The voltage across the inductor,

$$V_L = \omega L I \tag{13.2}$$

leads the current by 90°, and it will be presented along the positive y-axis. The voltage across the capacitor,

$$V_C = \frac{I}{\omega C} \tag{13.3}$$

lags the current by 90°, and is also presented on the vertical axis.

To obtain the resultant voltage, ε, we need to add voltages V_R, V_L, and V_C as vectors. The vector addition is illustrated in Fig. 13.1 (right). Because the vectors V_R and V_C or V_L form a right triangle, ε may be found from

$$\varepsilon^2 = V_R^2 + (V_L - V_C)^2. \tag{13.4}$$

Substituting Eqs. (13.1)–(13.3) into Eq. (13.4), leads to

$$\varepsilon = I\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} = IZ, \tag{13.5}$$

where $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$, and is called the impedance of the circuit. The phase difference between the current, I, and the line voltage, ε, is given by

$$\tan\phi = \frac{\omega L - \frac{1}{\omega C}}{R}. \tag{13.6}$$

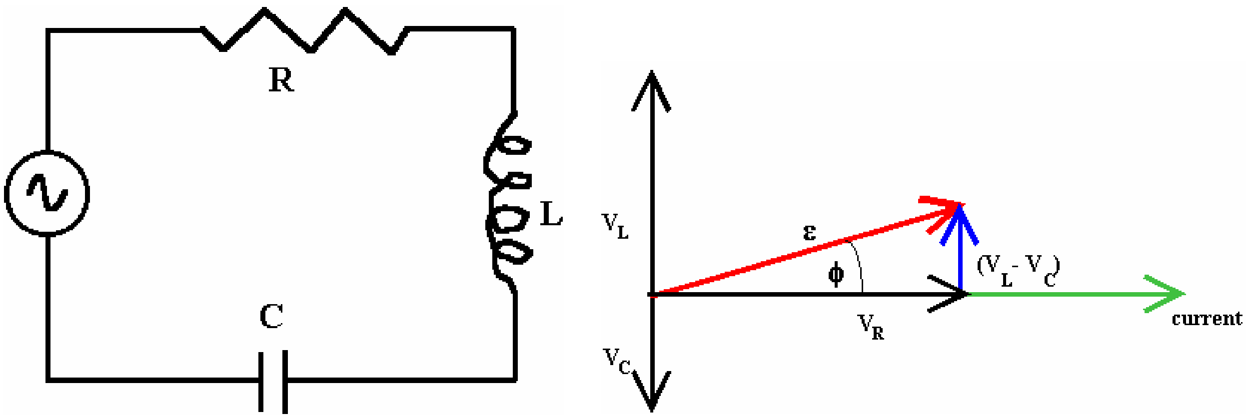

Figure 13.1: **AC circuits.** For an AC circuit containing a resistor, an inductor and a capacitor in series (left), the voltages across the three components are represented in a phase diagram (right).

From Eq. (13.6) it is seen that for $\omega L = 1/\omega C$ the phase difference, ϕ, is zero and the impedance, Z, equals R. This condition

$$\omega L = \frac{1}{\omega C} \tag{13.7}$$

is called resonance, and it can be reached by changing any of the quantities ω, C, or L. In this experiment, to reach resonance, you will change only C, while ω and L remain fixed. When the Z equals R, the current is maximum and the circuit is said to be in resonance.

In this experiment you will find the resonance by changing the capacitance of the system. The frequency ω is determined by the power supply, in this case it is 120π /s. ω measured in radians per second, and is related to the frequency $f = 60$ Hz, measured in cycles per second as $\omega = 2\pi f$. To find the resonance (remember the condition $\omega L = 1/\omega C$) you also need to know the values of L and C. Therefore, the experiment is divided into two parts, first, you will find inductance L, and second you will determine the value of C that leads to the resonance.

13.2 Procedure

The RLC circuit was built and installed inside a box with a transparent plastic cover so you can see all the connections inside, (Fig. 13.2). In addition there are several binding posts, which enable voltage measurements between different elements. **Do not touch metal parts of the posts with your hands**. To measure the voltage use special leads provided.

13.2.1 Finding the inductance

1. DISCONNECT THE POWER CORD.
2. Insert the plug into J2 and connect the leads to binding posts P4 and P5 on the box.
3. Set all capacitor switches to the open position.
4. Set the selector switch to the P (primary) position.

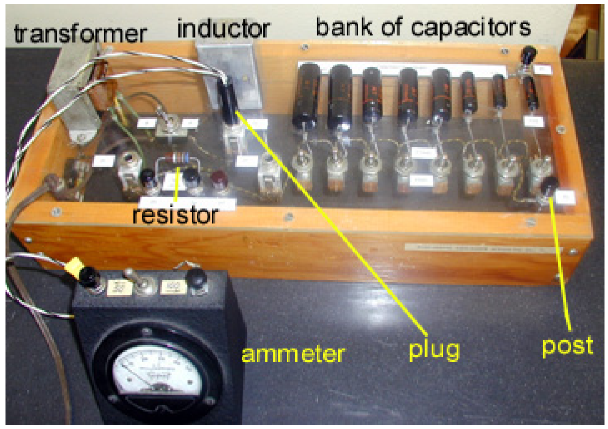

Figure 13.2: **RLC circuit.** Experimental setup of the RLC circuit with an ammeter attached.

5. Plug in the power cord and measure the voltage (remember to set the voltmeter to ACV) between P1 and P4. If this voltage is about 115 V, proceed to step 6. If it is not, disconnect power cord and reverse the connection to P4 and P5. Plug in power cord and measure the voltage between P1 and P4. If this voltage is not 115 V$\pm$10 V, ask for assistance before proceeding to step 6.

6. Measure the following voltages:
   - V_L, voltage across the inductor, between posts P1 and P5.
   - V_R , voltage across the resistor, between P4 and P5.
   - ε, line or input voltage, between P1 and P4.

7. Record the value of the resistor R, this value is marked on the plastic cover.

8. The actual phase diagram for the experimental circuit may differ from the theoretical diagram shown in Fig. 13.1 (right). This discrepancy is caused by the resistance of the wire, which was used to make an inductor. An inductor is a solenoid with many windings and the total length of the wire may be hundreds of meters. Also the wire used is typically very thin, which may result in a significant ohmic resistance of the inductor. Therefore, we need to find the resistance of the inductor, we will use symbol R_L to denote this value. Construct a vector diagram of the voltages as follows. Take the voltage V_R as a reference. Remember that this voltage is in phase with the current and draw vector, V_R, on a horizontal line as shown in Fig. 13.3.

   Use a suitable scale. Using A as a center, draw an arc of length V_L, and with the origin as a center, draw an arc of length ε. The intersection P, of these two arcs determines the vector diagram of the circuit. Drop a perpendicular from P onto the horizontal axis. The interval PB, which is perpendicular to the horizontal axis, represents the voltage due to the pure inductance. Remember that the voltage due to inductance is perpendicular to the voltage across the resistor. The interval OB represents the voltage due to the total resistance of the circuit, the resistors R and R_L. Since OA is the voltage across the resistor R, the interval

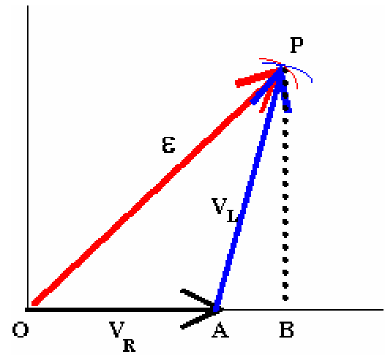

Figure 13.3: **Real phase diagram.** The actual phase diagram differs from the ideal case because of the resistance of the inductor.

AB represents the voltage due to the resistance of the inductor, R_L.

$$(AB) = IR_L. \tag{13.8}$$

Since $I = V_R/R$,

$$R_L = R(AB)/V_R. \tag{13.9}$$

The interval PB represents the voltage due to the inductance, L, of the inductor

$$(PB) = I\omega L \tag{13.10}$$

and

$$\omega L = R(PB)/V_R. \tag{13.11}$$

9. DISCONNECT THE POWER CORD. Remove the plug from J2 and set the selector switch to the S position. With the digital meter set to ohms, measure the resistance of the inductor, P1 and P3. You measured directly the ohmic resistance of the inductor, R_L. In the report, in the discussion section, explain why a value lower than that obtained above is obtained in this direct current measurement.

13.2.2 Finding the resonance

1. DISCONNECT THE POWER CORD.
2. Set the selector switch to the S position.
3. Insert the plug in J2 and connect the leads to the ammeter, as in Fig. 13.2. Set switch on the ammeter to the 50 mA position.
4. Plug in the power cord. Measure and record the current on the ammeter, the line voltage, ε, between posts P2 and P3, the voltage across the capacitors, V_C, across P1 and P2, and the voltage across the inductance, V_L, between P1 and P3, for various values of capacitance. By closing the switches you can get different values of resultant capacitance. The capacitors are connected in parallel and to find the resultant capacitance just add the values of individual

capacitances printed on the box. Start from zero and increase C in steps of 0.1 μF. You will observe that with increasing C the current increases, reaches the maximum, and then decreases. Near the maximum change the step to 0.05 μF and even to 0.02 μF. These additional points will enable better characteristics of the maximum, and thus the resonance conditions.

5. Graph the current, I, the line voltage, ε, the voltage across the capacitor, V_C, and the voltage across the inductor V_L as a function of capacitance, C, (on the horizontal axis). You will need 10 to 20 points to make good quality graphs.

13.3 Report

In this experiment graphs are very important, and all conclusions should be based on the analysis of the graphs. Two quantitative checks of the theory are possible. The maximum current occurs when $\omega L = 1/\omega C$, or when

$$C = \frac{1}{\omega^2 L}. \tag{13.12}$$

We will call this value the resonance capacitance and denote it as C_{res}. Remember that $\omega = 2\pi f$. Using $f = 60$ Hz, the frequency of the current and the value of the inductance, L, determined in section 2.1, calculate C_{res} and compare to the experimental value obtained from the graph. According to Eq. (13.5) the maximum value of the current is when $Z = R$.

$$I_{\text{max}} = \frac{\varepsilon}{RT} \tag{13.13}$$

where R_T is the total resistance of the circuit. Taking into account the small resistance of the ammeter, R_T is given by

$$R_T = R_L + R_M \tag{13.14}$$

where R_M is the resistance of the meter (measured with an ohmmeter) and R_L the resistance of the inductor obtained in section 2.1 (also measured with the ohmmeter). Calculate the maximum value of the current and compare with the value obtained in the experiment. In the introduction discuss applications of the series combinations of R, L and C. Also, explain what the electrical resonance is.

Lab 14

Transformer

14.1 Introduction

In this experiment you will study electrical characteristics of transformers. In early nineteenth century Oersted discovered that magnetic field always surrounds a current-carrying conductor. Later M. Faraday demonstrated that a change in magnetic flux, Φ, generates an electromotive force, ε:

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}. \tag{14.1}$$

The negative sign is in recognition of Lenzs law.

An iron-core transformer, Fig. 14.1, is an important device used in alternating current (AC) circuits, which involve these two discoveries. A transformer allows efficiently increase or decrease the line voltage. In its simplest form, the AC transformer consists of two coils of wire wound up around a core of iron as illustrated in Fig. 14.1.

The core directs the magnetic flux produced by alternating current in the first coil, called the primary, the other coil, called the secondary coil. The core has also another function. It can increase the magnitude of the magnetic flux. The changing flux through the secondary coil induces an alternating electromotive force of the same frequency on its terminals. Thus, electrical power may be transmitted. The efficiency of commercial transformers is usually better than 90%. For the sake of simplicity, we will first focus on an ideal transformer, which, by definition, has an efficiency of 100%. Later, we will consider energy losses in actual transformers.

14.1.1 Ideal transformers

When the magnetic flux through a coil of N turns changes at the rate $\mathrm{d}\Phi/\mathrm{d}t$, the induced electromotive force ε is given by

$$\varepsilon = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t}. \tag{14.2}$$

Thus, the voltage across the primary is expressed by

$$\varepsilon_p = -N_p\frac{\mathrm{d}\Phi}{\mathrm{d}t}. \tag{14.3}$$

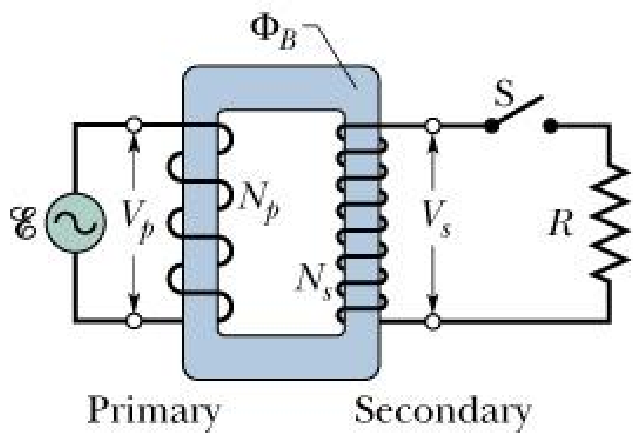

Figure 14.1: **Schematics of an ideal transformer.** N_p and N_s are numbers of turns in the primary and secondary coils, respectively.

Since it is an ideal transformer, all magnetic filed lines are remain within the iron core and the induced electromotive force in the secondary coil can be expressed as

$$\varepsilon_s = -N_s \frac{\mathrm{d}\Phi}{\mathrm{d}t}. \tag{14.4}$$

Often, instead of the electromotive force, we use the effective voltage V which is related to the electromotive force

$$V = \sqrt{2}\varepsilon \tag{14.5}$$

Solving Eq. (14.3) for $\mathrm{d}\Phi/\mathrm{d}t$ and substituting the result in Eq. (14.4), gives

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}. \tag{14.6}$$

When the primary coil has fewer turns than the secondary, the voltage across the terminals of the secondary coil will be greater than the primary voltage by the ratio N_s/N_p. Such a transformer is called a step-up transformer. When the number of turns in the secondary coil is less than in the primary, the secondary voltage is reduced and such a transformer is called a step-down transformer.

The ideal transformer has zero power loss, that is, the power input in the primary, $V_p I_p \cos\theta_p$, (θ is the phase angle between V and I) must be equal the power output in the secondary, $V_s I_s \cos\theta_s$. Since $\theta_p = \theta_s$, for the ideal transformer

$$V_p I_p = V_s I_s. \tag{14.7}$$

Combining Eq. (14.6) and Eq. (14.7) we find

$$I_p = I_s \frac{N_s}{N_p}. \tag{14.8}$$

This equation states that the current ratio is inversely proportional to the turn ratio of the coils. In welding operations, when heat is generated by high currents and for the safety reasons, the associated voltage is small, the step-down transformers are used. The step-up transformers are used at the generators to produce high voltages for efficient transmission of power. Step-down transformers are used at the other end of the transmission line to reduce the voltage to the convenient level.

14.1.2 Energy losses in transformers

Efficiency of a transformer is defined as a ratio of the output power to the input power. In commercial transformers the efficiency is usually better than 90%. The power losses in transformers are primarily due to loss of the flux, eddy currents, magnetization and demagnetization of the core, and resistance heating in the coils, and the change in the phase angle, θ_s.

To reduce the eddy currents the core is built from laminated and insulated sheets of the metal. The resistance of thin sheets of metal is increased and resistance of the core prevents the buildup of large eddy currents. To reduce heat losses in the coils they are built from metals of small resistance. Magnetization and demagnetization of the core requires energy. It is often called the hysteresis loss. To minimize this loss special metal alloys are used, usually silicon steel. Flux leakage is typically caused by breaks between elements of the core. To minimize these losses the cores are made from a single piece of a metal. In the experiment, the core is made of two parts, the U-shape core and the yoke.

14.2 Procedure

Assemble a transformer using two coils, one with 1000 turns and the other with 500 turns. Place the iron core in the shape of letter U into both coils and attach the iron yoke, with the bare side inward, to both ends of the U-core. Mount the transformer onto the breadboard and connect the primary coil to the power supply.

14.2.1 Transformer characteristics with no load on the secondary

1. Connect the terminals of the secondary coil to a voltmeter. **Make sure that the AC voltage and the range up to 20 volts are selected. Connect another voltmeter to the terminals of the primary of the transformer**. Increase the voltage of the power source and record both the primary and the secondary voltages in the table below.

Transformer measurements — no load on secondary.

V_p (V)	V_s (V)	V_s/V_p

2. Repeat the measurements with the coils exchanged and record the results below. In your report compare quotients V_s/V_p and N_s/N_p.

Transformer measurements — no load on secondary with coils exchanged.

V_p (V)	V_s (V)	V_s/V_p

3. Turn the power off and remove the yoke from the transformer, but leave the U-core inside. Repeat the last measurement for one arrangement of coils. Record the results in the table below.

Transformer with no yoke.

V_p (V)	V_s (V)	V_s/V_p

14.2.2 Transformer characteristics with a load on the secondary

1. Using the 500 turn coil as a secondary connect the circuit as diagrammed in Fig. 14.2 (top). Use 1.0 Ω resistor. Remember to connect the ammeters in series and voltmeters in parallel as shown in Fig. 14.2 (bottom). The digital ammeters must be connected to ports COM and 20 A and the knob must be set to measure AC current. Select the 20 A range. These are sensitive instruments, please be careful how you connect them. Ask the lab instructor to check your setup. Increase the voltage output of the power supply and record primary and secondary voltages and currents. Record data in the table below. Calculate the input power and the output power of the transformer and then its efficiency P_p/P_s.

Transformer with a load on the secondary.

V_p (V)	I_p (A)	V_s (V)	I_s (A)	V_s/V_p	I_s/I_p

2. (20484 only) Remove the 1.0 Ω resistor and leave the secondary open. It will correspond to an infinite resistance in the secondary. The input power corresponds to the power lost in the transformer due to hysteresis. Please read more about magnetic hysteresis in your textbook.

3. (20484 only) Set the input potential to about 20 V. Record the current in the primary. Next, short-circuit the secondary coil. The current is now limited by the impedance of the coil. To operate at the same input current as in the open-circuit test you will need to reduce the input voltage. The low voltage and the low current in the primary generate very low magnetic field and losses due to hysteresis can be ignored. The power that you find for the short-circuited transformer represents the Joule power lost due to resistance in the winding.

14.3 Report

In the report include the following:

1. Explain the nature of eddy currents.

2. Compare quotients V_s/V_p and N_s/N_p. Are these ratios similar?

3. Compare the values I_s/I_p with the ratio of the turns, N_s/N_p. Are these quotients similar?

4. Why is the efficiency of the transformer so low? The commercial transformers have efficiency better than 90%. Suggest how to improve the efficiency in the experiment.

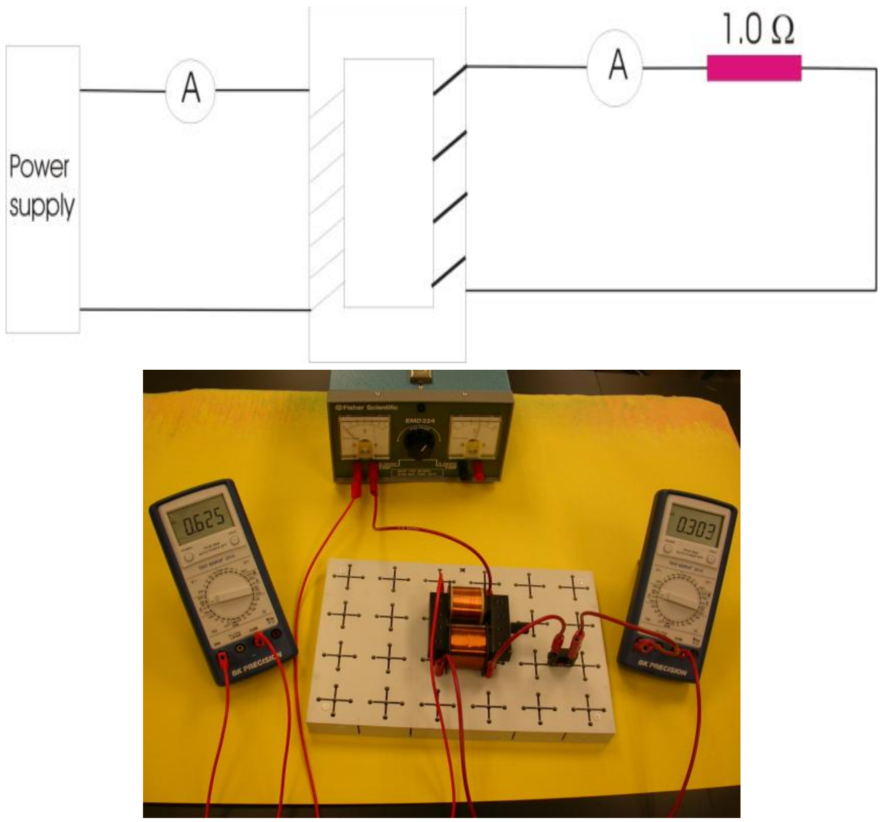

Figure 14.2: **Experimental setup for lab 10.** The schematics (top) and a photograph (bottom) of the experimental setup to measure input and output power. The voltmeter to measure potential across the resistor is optional.