Physics Laboratory Manual for Engineering Undergraduates

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CONTENTS

Instructions for Laboratory

- The objective of the laboratory is learning. The experiments are designed to illustrate phenomena in different areas of Physics and to expose you to measuring instruments. Conduct the experiments with interest and an attitude of learning.
- You need to come well prepared for the experiment
- Work quietly and carefully (the whole purpose of experimentation is to make reliable measurements!) and equally share the work with your partners.
- Be honest in recording and representing your data. Never make up readings or doctor them to get a better fit for a graph. If a particular reading appears wrong repeat the measurement carefully. In any event all the data recorded in the tables have to be faithfully displayed on the graph.
- All presentations of data, tables and graphs calculations should be neatly and carefully done.
- Bring necessary graph papers for each of experiment. Learn to optimize on usage of graph papers. For example, in Experiment 16 (Planck's constant) you do not need three separate sheets to represent the graphs of $\ln I_{ph}$ vs. T^{-1} for the three different filters. All the three graphs can be accommodated on a single graph sheet.
- Graphs should be neatly drawn with pencil. Always label graphs and the axes and display units.
- If you finish early, spend the remaining time to complete the calculations and drawing graphs. Come equipped with calculator, scales, pencils etc.
- Do not fiddle idly with apparatus. Handle instruments with care. Report any breakage to the Instructor. Return all the equipment you have signed out for the purpose of your experiment.

Bibliography

Here is a short list of references to books which may be useful for further reading in Physics or instrumentation relevant to the experiments. Also included are some references to books of general interest with regard to science and experimentation.

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Experiment 1

Error Analysis and Graph Drawing

I. Introduction:

1.1 It is impossible to do an experimental measurement with perfect accuracy. There is always an uncertainty associated with any measured quantity in an experiment even in the most carefully done experiment and despite using the most sophisticated instruments. This uncertainty in the measured value is known as the error in that particular measured quantity. There is no way by which one can measure a quantity with one hundred percent accuracy. In presenting experimental results it is very important to objectively estimate the error in the measured result. Such an exercise is very basic to experimental science. The importance of characterizing the accuracy and reliability of an experimental result is difficult to understate when we keep in mind that it is experimental evidence that validate scientific theories. Likewise, reliability and accuracy of measurements are also deeply relevant to Engineering.

The complete science of error analysis involves the theory of statistics (see Ref. 1,2) and is too involved to present here. This short presentation is intended to introduce the student to some basic aspects of error analysis and graph drawing, which it is expected that the student will then put into practice when presenting his/her results of the coming experiments.

I.2 When a measurement of a physical quantity is repeated, the results of the various measurements will, in general, spread over a range of values. This spread in the measured results is due to the errors in the experiment. Errors are generally classified into two types: *systematic (or determinate)* errors and *random (or indeterminate)* errors. A systematic error is an error, which is constant throughout a set of readings. Systematic errors lead to a clustering of the measured values around a value displaced from the "true" value of the quantity. Random errors on the other hand, can be both positive or negative and lead to a dispersion of the measurements around a mean value. For example, in a time period measurement, errors in starting and stopping the clock will lead to random errors, while a defect in the working of the clock will lead to systematic error. A striking example of systematic error is the measurement of the value of the electric charge of the electron 'e' by Millikan by his Oil Drop method. Millikan underestimated the viscosity of air, leading to a lower value for his result

$$e = (1.591 \pm .002) \times 10^{-19}\ \text{C} \quad \text{------------------------------------} \ \mathbf{(1)}$$

Compare this with a more modem and accurate value (Cohen and Taylor 1973, Ref. 3)

$$e = (1.602\ 189 \pm 0.000\ 005) \times 10^{-19}\text{C.} \quad \text{----------------------} \ \mathbf{(2)}$$

Systematic errors need to be carefully uncovered for the particular experimental set-up and eliminated by correcting the results of the measurements.

I.3 Random errors are handled using statistical analysis. Assume that a large number (N) of measurements are taken of a quantity Q giving values Q1, Q2, Q3…QN. Let Q be the mean value of these measurements

$$\overline{Q} = \tfrac{1}{N}\sum_{i=1}^{N} Q_i \qquad i = 1 \quad \text{---------------------------------} \ \mathbf{(3)}$$

and let 'd' be the deviation in the measurements

$$d = \sqrt{\tfrac{1}{N}\sum_{i=1}^{N}(Q_i - \overline{Q})^2} \quad \text{---} \ \mathbf{(4)}$$

The result of the measurement is quoted (assuming systematic errors have been eliminated) as

$$Q = \overline{Q} \pm d \quad \text{--} \ \mathbf{(5)}$$

The error ΔQ in the quantity is then taken to be the deviation d. (This is called the *standard error* in Q)

In a single measurement of a physical quantity, the error can be estimated as the least count (or its fraction) of the instrument being used.

As an example, the result of a measurement of the radius of curvature R, of a plano-convex could be quoted as

$$R = 140 \pm 0.2\ \text{cm.} \quad \text{-----------------------------} \ \mathbf{(6)}$$

This means that we expect that the value of R being in the range 139.8 to 140.2 cm. Note however, that this does not mean that the "true" value of R necessarily lies in this range, only that there is a possibility that it will do so.

The error in measurement can also be quoted as a percent error

$$\frac{\Delta Q}{\bar{Q}} \times 100 = \frac{d}{\bar{Q}} \times 100 \qquad \text{---} \ \mathbf{(7)}$$

For example, the percentage error in R is 0.143 %.

I.4 Combination of errors:

Many times the value of a measured quantity may depend on other intermediate measured quantities. For example we could have a quantity Q which is a function F of a number of independent intermediate variables say x, y and z i.e.,

$$Q = F(x,y,z) \text{--} \mathbf{(8)}$$

If the indeterminate errors related to x, y, z are $\Delta x, \Delta y$ and Δz respectively, then the error in Q can be calculated as

$$\Delta Q = (\partial F/\partial x)\Delta x + (\partial F/\partial y)\Delta y + (\partial F/\partial z)\Delta z = a\Delta x + b\Delta y + c\Delta z \quad \text{------------} \ \mathbf{(9)}$$

An important characteristic of errors is that the total error in a function, due to different variables is always additive. Therefore, more accurately, the error ΔQ is calculated as

$$\Delta Q = \left|\frac{\partial F}{\partial x}\Delta x\right| + \left|\frac{\partial F}{\partial y}\Delta y\right| + \left|\frac{\partial F}{\partial z}\Delta z\right| = |a\,\Delta x| + |b\,\Delta y| + |c\,\Delta z| \text{--------------} \ \mathbf{(10)}$$

$$= \Delta Q_A + \Delta Q_B + \Delta Q_C$$

As an example, consider the quantity $Q = x + y$.

If the error in x (i.e., Δx) is negative and that in y (i.e., Δy) is positive, the total error in the quantity x+y will be $|\Delta x| + |\Delta y|$ not $\Delta x + \Delta y$, which means combination of errors always lowers the quality of the experimental data.

In fact, using statistical analysis (where the. error is defined as the root mean square deviation from the mean) the correct expression for the error in Q can be shown to be $\Delta Q = \sqrt{(\Delta x)^2 + (\Delta y)^2}$.

In general we have the rule that (following statistical analysis) if Q is a function of x, y, z,…., then

$$(\Delta Q)^2 = (\Delta Q_x)^2 + (\Delta Q_y)^2 + (\Delta Q_{z)})^2 \ldots\ldots\ldots\ldots \text{--------------------------} \quad \mathbf{(11)}$$

where, $\Delta Q_x = (\frac{\partial Q}{\partial x})\Delta x$; $\Delta Q_y = (\frac{\partial Q}{\partial y})\Delta y$; $\Delta Q_z = (\frac{\partial Q}{\partial z})\Delta z$ etc.

The following table summarizes the results for combining errors for some standard functions. Try to derive some of these results.

S.No	Function	Error in ΔQ or Fractional error ΔQ/Q
1.	$Q = x + y$	$\Delta Q = \sqrt{(\Delta x)^2 + (\Delta y)^2}$
2.	$Q = x - y$	$\Delta Q = \sqrt{(\Delta x)^2 + (\Delta y)^2}$
3.	$Q = xy$	$\left(\frac{\Delta Q}{\overline{Q}}\right)^2 = \left(\frac{\Delta x}{\overline{x}}\right)^2 + \left(\frac{\Delta y}{\overline{y}}\right)^2 \Rightarrow \left(\frac{\Delta Q}{\overline{Q}}\right) = \sqrt{\left(\frac{\Delta x}{\overline{x}}\right)^2 + \left(\frac{\Delta y}{\overline{y}}\right)^2}$
4.	$Q = x/y$	$\left(\frac{\Delta Q}{\overline{Q}}\right)^2 = \left(\frac{\Delta x}{\overline{x}}\right)^2 + \left(\frac{\Delta y}{\overline{y}}\right)^2 \Rightarrow \left(\frac{\Delta Q}{\overline{Q}}\right) = \sqrt{\left(\frac{\Delta x}{\overline{x}}\right)^2 + \left(\frac{\Delta y}{\overline{y}}\right)^2}$
5.	$Q = x^n$	$\frac{\Delta Q}{\overline{Q}} = n\frac{\Delta x}{x}$
6.	$Q = \ln x$	$\Delta Q = \frac{\Delta x}{\overline{x}}$
7.	$Q = e^x$	$\frac{\Delta Q}{\overline{Q}} = \Delta x$

II. Drawing of best fit straight line graph:

To draw the best fit straight line graph through a set of scattered experimental data points we will follow a standard statistical method, known as *least squares fit* method.

Let us consider a set of N experimental data points (x_1,y_1), (x_2,y_2), …….(x_N,y_N). It is well known that a straight-line graph is described by the equation

$$y = mx + C. \qquad \text{---} \quad \textbf{(12)}$$

We ask the question: how are the slope 'm' and the y-intercept 'c' to be determined such that a straight line best approximates the curve passing through the data points? Let $S_i = y_i - m_i x_i - c$ be the deviation of any experimental point P (xi, yi), from the best fit line. Then, the gradient 'm' and the intercept 'c' of the best fit straight line has to be found such that the quantity

$$S=\sum_i (y_i - m x_i - c)^2$$

is a minimum . We require

$$\frac{\partial S}{\partial m}=-2\sum x_i (y_i - m x_i - c)=0 \text{ and } \frac{\partial S}{\partial c}=-2\sum (y_i - m x_i - c)=0,$$

which give,

$$m\sum x_i^2 + c\sum x_i = \sum x_i y_i \quad \text{and} \quad m\sum x_i + Nc = \sum y_i .$$

The second equation can be written as as $\bar{y}=m\bar{x}+c$, where $\bar{y}=\frac{1}{N}\sum y_i$ and $\bar{x}=\left(\frac{1}{N}\sum x_i\right)$ showing that the best fit straight line passes through the centroid $(\bar{x},\bar{y})$ of the points (x_i , y_i) .The requires values of m and c can be calculated from the above two equations to be

$$m=\frac{\sum (x_i-\bar{x})y_i}{\sum (x_i-\bar{x})^2} \quad \text{and} \quad c=\bar{y}-m\bar{x} \text{ ----------------------------------}\textbf{(13)}$$

The best-fit straight line can be drawn by calculating m and c from above. A graphical method of obtaining the best fit line is to rotate a transparent ruler about the centroid so that it passes through the clusters of points at the top right and at the bottom left. This line will give the maximum error in m, $(\Delta m)_1$, on one side. Do the same to find out the maximum error in m, $(\Delta m)_2$ on the other side. Now bisect the angle between these two lines and that will be the best-fit line through the experimental data.

What are the errors in the gradient and intercept due to errors in the experimental data points? The estimates of the standard errors in the slope and intercept are

$$(\Delta m)^2 \approx \frac{1}{D}\frac{\sum S_i^2}{N-2} \quad \text{and} \quad (\Delta c)^2 \approx \left(\frac{1}{N}+\frac{\bar{x}^2}{D}\right)\frac{\sum S_i^2}{N-2},$$

where $D=\sum (x_i-\bar{x})^2$ and S_i is the deviation ,$S_i = y_i - m x_i - c$.

II.1. Presentation of error associated with experimental data in a graph.

Let us consider a function, y = f(x), where x is an independent parameter which in the hand of the experimentalist during performing the experiments and y is the experimental data which is having a value depending upon the x and the instruments. Let the error associated with x be ±Ax and that for y be ±Ay. One can represent ±Ax and ±Ay with the experimental data point P(x,y) on the graph paper. To do that, first plot P(x,y) on the graph paper, then draw a vertical line parallel to y axis about the point P(x,y) of length 2Ay. So upper half of the line represents the error +Ay and the lower half represents -Ay error. To present ±Ax, draw horizontal lines at the two ends of the vertical line of length 2Ax each. The whole presentation is now giving the errors associated with the experimental point P(x,y).

Figure 1 is an example of experimental data of resonance absorption of γ – ray experiment (Mössbauer spectroscopy) with error associated with each experimental data. The solid lines give the fitted curve through the experimental data. Note that the error in the variable along horizontal axis is not shown.

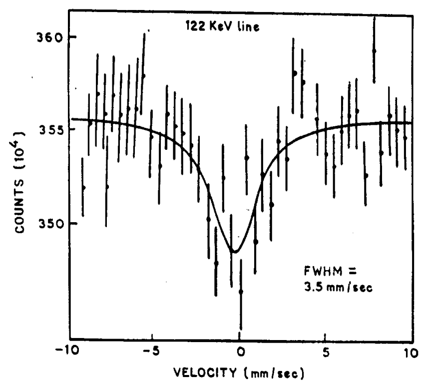

Fig 1

II.2 Use of graphs in experimental physics:

In practical physics, the graph of the experimental data is most important in improving the understanding of the experimental results. Moreover from the graphs one can calculate unknowns related to the experiments and one can compare the experimental data with the theoretical curve when they are presented on same graph. There are different types of graph papers available in market. So, one should choose the appropriate type of graph paper to present their experimental results in the best way depending upon the values of the experimental data and the theoretical expression of the functions. To understand all those some of the assignments are given below in addition to those we discussed before.

III. Exercises and Viva Questions

Radius of curvature(cm)
130.121
130.126
130.139
130.148
130.155
130.162
130.162
130.169

1. What is the general classification of errors? Give an example of each. How are they taken care of?
2. What is the meaning of standard error? Calculate the standard error for the hypothetical data given in the adjacent table. Express the quantity as in eq(5) i.e. $R = \overline{R} \pm d$
3. What is the percentage error in Millikan's experiment of the charge of the electron: $e = (1.591 \pm 0.002) \times 10^{-19}$ C?
4. What is the error in the volume of a cube $V=L^3$ if the error in L is 0.01m? If L is measured as L= 2 ± 0.01, express the value of V in a similar manner.
5. A small steel ball-bearing rests on top of a horizontal table. The radius (R) of the ball is measured using a micrometer screw gauge (with vernier least count 0.05 mm) to be 2.15 mm. The height of the table is found using an ordinary meter scale to be 90 cm. What is the height of the center of the steel ball from the floor (include the error)?.
6. Let Q = x - y, where x= 100 ± 2 and y = 96 ± 2 .Calculate Q (express the result with the error included)
7. Consider the quantity Q = x / y. If x = 50 ± 1 and y = 3 ± 0.2. Calculate Q (express the result with the error included)
8. In an experiment involving diffraction of sodium light using a diffraction grating, the double lines are unresolved at first order and a single spectral line is seen at an angle of 13^0. If the least count of the vernier of the telescope is $1^{/,}$ what will be the error in the calculated value of the grating constant d? (Principal maxima of a grating occurs at angles θ such that $d \sin \theta = m\lambda$. The wavelength separation between the sodium double slit lines is 6 A^0)
9 Consider an experiment to measure the gravitational acceleration 'g' by measuring the time period of a simple pendulum. What are the possible sources of systematic error in this experiment?
10. "If there are always errors in any measurement then there is nothing like the 'true' value of any measured quantity ". Comment on this statement. In what sense then do you understand the values of 'physical constants' to be constants?

References:

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Experiment 1

Error Analysis and Graph Drawing

Assignments:

1. Experimental data (in arbitrary units) of some experiment is given below :

x	-10	4	10	16	20	35	40	32	40	45	53	60	65	70	80	85
y	-17	-20	-30	-17	-35	-2	-19	-3	-4	10	11	24	20	30	37	47
x	100	115	120	122	129	133	140	141	150	151	154	157	160	170	172	183
y	50	80	77	79	80	83	80	100	90	113	102	110	100	106	101	200

(a) Assuming 10% of error in Y values, plot the data on preferred graph paper showing the errors in terms of error bars.

(b) Calculate the slope and intercept of the best fit graph .Draw the best fit graph on the above graph.

2. The expression of refractive index of a prism id given by the following relation: $\mu = \dfrac{\sin\left(\dfrac{A+D}{2}\right)}{\sin(A/2)}$. Assuming the error of A and D as ΔA and ΔD, express the error of μ. Here 'A' is the angle of the prism and 'D' is the angle of deviation.

3. The relation between two independent variables X and Y is given as the empirical expression $Y = a X + b X^3$ .The experimental data for X and Y are given below :

X : 0.130 0.192 0.232 0.263 0.299 0.326 0.376 0.392 0.416 0.454 0.471 Y : 0.280 0.405 0.504 0.593 0.685 0.749 0.922 0.986 1.049 1.192 1.256 X : 0.492 0.533 0.541

Y : 1.332 1.51 1.531

Rearrange the equation to plot the graph in simpler form. (Hint: Plot Y/X vs X^2). (Why?) .Then find out the constants 'a' and 'b' from the graph .Try to co-relate the expression with some practical experiment in physics and give your comments about the constants.

4. Expression of some function is given by, $Y = a X^{b}$, where 'a', 'b' are unknown .Use the following experimental data to find out the constants by plotting an appropriate graph of Y vs. X. Try to co-relate the above expression with some practical experiment in physics and give your comments about the constants.

X :	465	599	688	720	878	922	1025	1220	1311	1410	1509
Y :	2589	7106	12132	15680	25090	40616	60142	117626	168086	222876	287091

5. The ionic conductivity of (C) of a crystal is given as a function of temperature (T) by the equation, $C = C_0 \exp(+E/kT)$ where k is Boltzmann constant. (T is in Kelvin and C is in $CX10^7$ cgs unit)

T :	746	805	825	853	875	885	915	952	965	990
$CX10^7$:	1.82	2.90	5.85	8.40	19.1	32.7	66.1	120	245	418

Plot the experimental data on suitable graph paper and find out the value of C_0 and E.

(Four graph papers required).

Experiment 2

Coupled Pendulum

Apparatus:

Two compound pendulums, coupling spring, convergent lens, filament bulb on stand, screen on stand, stop clock.

Purpose of experiment:

To study normal modes of oscillation of two coupled pendulums and to measure the normal mode frequencies.

Basic Methodology:

Two identical compound pendulums are coupled by means of spring .Normal mode oscillations are excited and their frequencies are measured.

I. Introduction:

I.1 The reason why the study of simple harmonic motion is important is the very general manner in which such a motion arises when we want the response of a system to small deviation from the equilibrium configuration .This happens for a wide variety of systems in Physics and Engineering.

The response of a system to small deformations can usually be described in terms of individual oscillators making up the system. However, the oscillators will not have independent motion but are generally coupled to that of other oscillators. Think for example of vibrations in a solid. A solid can be thought of as being composed of a lattice of atoms connected to each other by springs. The motion of each individual atom is coupled to that of its neighboring atoms.

The description of a system of coupled oscillators can be done in terms of its **normal modes.** In a coupled system the individual oscillators may have different natural frequencies. A normal mode motion of the system however will be one in which all the individual oscillators oscillate with the same frequency (called the normal mode frequency) and with definite phase relations between the individual motions. If a system has n degrees of freedom (i.e. has n coupled oscillators) then there will be n normal modes of the system. A general disturbance of the system can be described in terms of a superposition of normal mode vibrations. If a single oscillator is excited, then eventually the energy gets transferred to all the modes.

I.2 In this experiment we will study some of the above features in the simple case of two coupled compound pendulums. The system studied in the experiment consists of two identical rigid pendulums, A and B. A linear spring couples the oscillations of the two pendulums. A schematic diagram of the system is given in Figure 1.

The motion of the two pendulums A and B can be modeled by the following coupled differential equations (θ_A and θ_B are the angular displacements of A and B, and I being their moments of inertia)

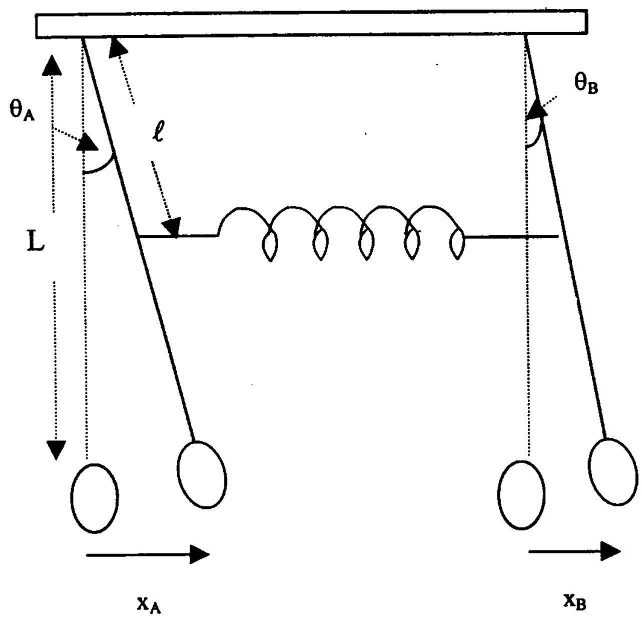


Fig 1

The equations of motion of the two physical pendulums are easily obtained. Let θ_A and θ_B be the angular displacement, and x_A and x_B the linear displacements of the two pendulums respectively .The compression of spring will be $(x_A - x_B) = \frac{l}{L}$ .where l is the distance between the point of suspension and the point where the spring is attached and L is the length of the pendulum. The equation for pendulum A thus will be

$$I \frac{d^2 \theta_A}{dt^2} = -m\, g\, L_{CM} \sin\theta_A - k\,(x_A - x_B)\frac{l}{L} l \cos\theta_A \quad \text{-----------------------}$$

(1)

where the first term on the right hand side is the restoring torque due to gravity (L_{CM} being the distance between the point of suspension and the position of the center of mass of pendulum A) while the second term that due to the spring force .Assuming the mass attached to the pendulum A to be sufficiently heavy we can equate L_{CM} and L. We also consider small displacements θ_A, so that $\sin\theta_A \approx \theta_A$ and $\cos\theta_A \approx 1$. Substituting $\theta_A = x_A / L$ and using the above approximations, we obtain the following equation of motion for linear displacement x_A:

$$\frac{d^2 x_A}{dt^2} = -\left(\frac{m\, g\, L}{I}\right) x_A - k(x_A - x_B)\frac{l^2}{I} \quad \text{--------------------------------------}$$

(2)

Like wise the equation for is

$$\frac{d^2 x_B}{dt^2} = -\left(\frac{m\, g\, L}{I}\right) x_B - k(x_A - x_B)\frac{l^2}{I} \quad \text{--------------------------------------}$$

(3)

Equations (2) & (3) are coupled, i.e. the equation for x_A involves x_B and vice – versa. Without the coupling, i.e. in the absence of the spring, x_A and x_B would be independent oscillations with the natural frequency $\omega_0 = \sqrt{(m\,g\,L)/\,I}$.

I.3 It is easy to find uncoupled equations describing the normal modes of the system. Define the variables

$$x_1 = x_A + x_B \quad ; \quad x_2 = x_A - x_B \quad \textbf{---(4)}$$

Adding and subtracting eqs(2) and (3) we obtain equations for the variables x_1 and x_2 as

$$\frac{d^2\,x_1}{dt^2} = -\left(\frac{m\,g\,L}{I}\right)x_1 \quad \textbf{-- (5)}$$

$$\frac{d^2\,x_2}{dt^2} = -\left(\frac{m\,g\,L}{I}\right)x_2 - 2\frac{k\,l^2}{I}\,x_2 \quad \textbf{-- (6)}$$

Note that the equations for x_1 and x_2 are uncoupled .The variables x_1 and x_2 describe independent oscillations and are the two normal modes of the system .The general solution to these equations will be

$$x_1(t) = A_1\cos(\omega_1\,t + \varphi_1) \quad ; \quad x_1(t) = A_2\cos(\omega_2\,t + \varphi_2) \quad \textbf{---------------------- (7)}$$

(A_1, A_2 being the amplitudes of the two modes and φ_1 and φ_2 arbitrary phases).The corresponding natural frequencies are the normal mode frequencies:

$$\omega_1 = \omega_0 \quad ; \quad \omega_2 = \sqrt{\omega_0^2 + \frac{2\,k\,l^2}{I}} = \omega_0\sqrt{1 + \frac{2\,k\,l^2}{m\,g\,L}} \quad \textbf{------------------------- (8)}$$

where $\omega_0 = \sqrt{\frac{m\,g\,L}{I}}$ is the natural frequency of each uncoupled pendulum.

It is instructive that to visualize the motion of the coupled system in these normal modes. If we excite only the first normal mode, i.e. $x_1(T) \neq 0$, but $x_2(t) = 0$ at all times, the individual motions of pendulums A and B will be

$$x_A(t) = \frac{1}{2}\big(x_1(t) + x_2(t)\big) = \frac{A_1}{2}\cos(\omega_1 t + \varphi) = x_B(t) = \frac{1}{2}\big(x_1(t) - x_2(t)\big) \textbf{------------------ (9)}$$

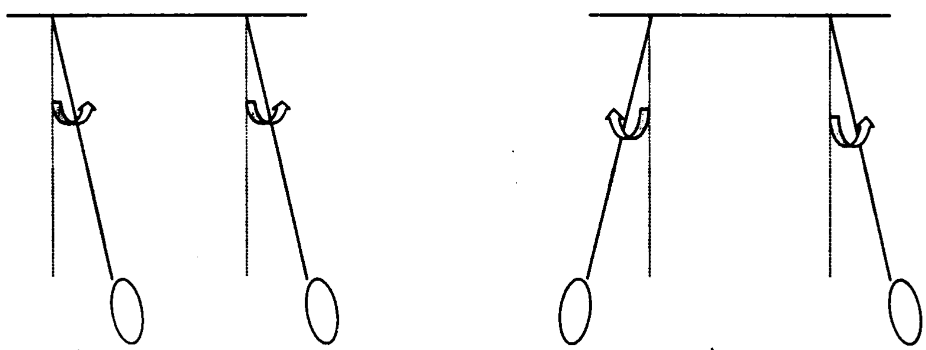
Note that in this mode $x_A = x_B$ .This describes a motion in which both pendulums move in phase with the same displacement and frequency ω_1.

On other hand if the second mode id excited, i.e. $x_1(t) = 0$ for all times and $x_2(t) \neq 0$ the individual motions are

$$x_A(t) = \frac{1}{2}\big(x_1(t) + x_2(t)\big) = \frac{A_1}{2}\cos(\omega_2\,t + \varphi_2) = -x_B(t) = -\frac{1}{2}\big(x_1(t) - x_2(t)\big) \text{--}\textbf{------}$$

(10)

In this mode the displacements of the pendulums are always opposite ($x_1(t) = - x_2(t)$). Their motions have the same amplitude and frequency (= ω_2) but with a relative phase difference of π . Figure 2 shows the motions in the normal modes.



I.4. A general motion of the coupled pendulums will be be a superposition of the motions of the two normal modes:

$$x_A(t) = \frac{1}{2}\left[A_1 \cos(\omega_1 t + \varphi_1) + A_2 \cos(\omega_2 t + \varphi_2)\right]$$

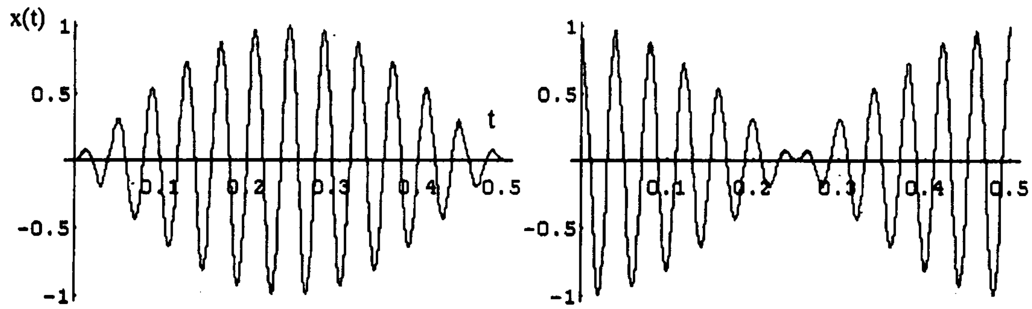
$$x_B(t) = \frac{1}{2}\left[A_1 \cos(\omega_1 t + \varphi_1) - A_2 \cos(\omega_2 t + \varphi_2)\right] \quad \text{--------------------------------} \ \mathbf{(11)}$$

For a given initial condition the unknown constants (two amplitudes and two phases) can be solved. Consider the case where the pendulum A is lifted to a displacement A at t = 0 and released from rest while B remains at its equilibrium position at t = 0. The constants can be solved (see Exercise 4) to give the subsequent motions of the pendulums to be

$$x_A(t) = A\cos\left(\frac{\omega_2 - \omega_1}{2} t\right)\cos\left(\frac{\omega_2 + \omega_1}{2} t\right)$$

$$x_B(t) = A\sin\left(\frac{\omega_2 - \omega_1}{2} t\right)\sin\left(\frac{\omega_2 + \omega_1}{2} t\right) \quad \text{----------------------------------} \ \mathbf{(12)}$$

The motions of the pendulums A and B exhibit a typical beat phenomenon. The motion can be understood as oscillations with a time period $4\pi / (\omega_2 + \omega_1)$ and a sinusoid ally varying amplitude A(t) with the amplitude becoming zero with a period of $4\pi / (\omega_2 - \omega_1)$**.** As an example, Figure 3(a),3(b) show plots of $x(t)=\sin(2\pi t)\sin(50\pi t)$ and $x(t)=\cos(2\pi t)\cos(50\pi t)$ vs. t respectively.



II. Setup and Procedure:

1. Uncouple the pendulums. Set small oscillations of both pendulums individually. Note the time for 20 oscillations and hence obtain the average time period for free oscillations of the pendulums and the natural frequency ω_0.
2. Couple the pendulums by hooking the spring at some position to the vertical rods of the pendulums. Ensure that the spring is horizontal and is neither extended nor hanging loose to begin with.
3. Switch on the bulb and observe the spot at the centre of the screen.
4. Excite the first normal mode by displacing both pendulums by the same amount in the same direction. Release both pendulums from rest. The spot on the screen should oscillate in the horizontal direction.
5. Note down the time for 20 oscillations and hence infer the time period T, and frequency ω_1 of the first normal mode.
6. With the spring at the same position excite the second normal mode of oscillation by displacing both pendulums in the opposite directions by the same amount and then releasing them from rest.
7. The spot on the screen should oscillate in the vertical direction. Note down the time for 20 oscillations and hence infer the time period T_2 and frequency ω_2 **.**
8. Repeat these measurements for the spring hooked at 3 more positions on the vertical rods of the pendulums.

(Part
B)

9. For any one position of the spring (already chosen in Part A), now displace any one pendulum by a small amount and (with the other pendulum at its equilibrium position) release it from rest. Observe the subsequent motion of the pendulums. Try to qualitatively correlate the motion with the graph shown in Fig. 3. Measure the time period T of ***individual*** oscillations of the pendulum A and also the time period ΔT between the times when A comes to a total stop. Repeat these measurements three times for accuracy. Infer the time periods T_1, and T_2 of the normal modes from T and ΔT and compare with earlier results.

(Note: Your measurements will be more accurate only if you choose t somewhat smaller than the total length L, i.e. choose a position of the coupling spring which is intermediate in position).

III. **Exercises and Viva Questions**

1. What are normal modes of a system? How many normal modes will a system posses?
2. Infer the normal mode frequencies for the coupled pendulum by directly considering the motion in the two modes as shown in fig 2.
3. Qualitatively explain why the first normal mode frequency is independent of the position of the spring while the second normal mode frequency increases with l, the distance of the spring from the point of support.
4. For the cases where pendulum A is lifted and released from rest derive unknown constants A_1, A_2 , φ_1 , φ_2 in equation (11) to obtain the solution equation (12).
5. Explain the effect of damping on the motion. Redraw figure 3 qualitatively if damping is present.
6. List all the approximations made in the theory of the double pendulum treated in the theory as against the actual apparatus used and estimate the error introduced. Also, consider possible sources of random errors while conducting the experiment.
7. Explain why the spot on the screen moves the way it does, i.e. horizontally when the 1^{st} normal mode is excited and vertically when the 2^{nd} normal mode is excited.
8. Describe and explain the motion of the spot on the screen when only pendulum is displaced.
9. In part B, derive the expressions for the normal modes ω_1 and ω_2 from the T and ΔT .What is the reason that the procedure asks you to choose a value of l small compared to L for better accuracy?
10. Give some more examples of coupled oscillations from Physics or Engineering systems.

References

1. “Vibrations and Waves”, A.P .French, Arnold-Heinemann, New Delhi, 1972.
2. “The elements of Physics”, I.S.Grant and W.R.Phillips ,Oxford University Press, Oxford

Coupled Pendulums

Observations and Results

Position of spring from pivot l (cm)	Mode 1			Mode 2		
	Time(sec) (for 20 oscillations)	Period T_1 (sec)	Angular frequency ω_1 (sec $^{-1}$)	Time(sec) (for 20 oscillations)	Period T_2 (sec)	Angular frequency ω_2 (sec $^{-1}$)

<u>Table of Observations for Part B</u>

Position of spring l = __________________ cm *(Note that this has to be one of the values Chosen in PART A)*

S.No	Time period between successive oscillations T (sec)	Time period between successive stops ΔT (sec)	Average T (sec)	Average ΔT (sec)	Angular frequency $\omega_1 = 2\pi\left(\frac{1}{T} - \frac{1}{\Delta T}\right)$	Angular frequency $\omega_2 = 2\pi\left(\frac{1}{T} + \frac{1}{\Delta T}\right)$
1						
2						
3						

Calculations and Graph

1. On the same graph paper plot ω_1^2 / ω_0^2 and ω_2^2 / ω_0^2 vs. l^2 .
2. Obtain the slope of the graph of ω_1^2 / ω_0^2 vs. l^2 and hence obtain the spring constant k of the coupling spring

Slope = 2 k / (mgL) = ______________________

Spring constant k = ________________________dynes / cm

<u>Conclusions:</u>

(One graph paper required).

Experiment 3

Study of Small Oscillations using a Bar Pendulum

Apparatus:

A bar pendulum with holes for hanging, Wall support for hanging, stop clock, meter scale, knife edge for measuring the center of mass of the bar.

Purpose of experiment:

To measure the acceleration due to gravity (g) by small oscillations of a bar pendulum.

Theory

The period of oscillations T of a body constrained to rotate about a horizontal axis for small amplitudes is given by the expression

$$T = 2\pi\left(\frac{I}{mgd}\right)^{\frac{1}{2}} \qquad (1)$$

where m is mass of the body , d is the distance between center of mass (CM) and the axis of rotation and I is the moment of inertia (MI) about the axis of rotation given by (from parallel axis theorem)

$$I = I_0 + md^2 \qquad (2)$$

where, I_o is the moment of inertia about parallel axis through center of mass .
If k is the radius of gyration (i.e. $I_0 = mk^2$). Then from eqs (1) and (2)

$$T^2 d = \frac{4\pi^2}{g}\left(k^2 + d^2\right) \qquad (3)$$

By recording the period of oscillations T as a function d we can determine the values of gravitational acceleration g as well as moment of inertia I_o of the body . The plot of T Vs d , shows a minimum time period at $d = K$,given by

$$T_{\min} = 2\pi\left(\frac{2k}{g}\right)^{\frac{1}{2}} \qquad (4)$$

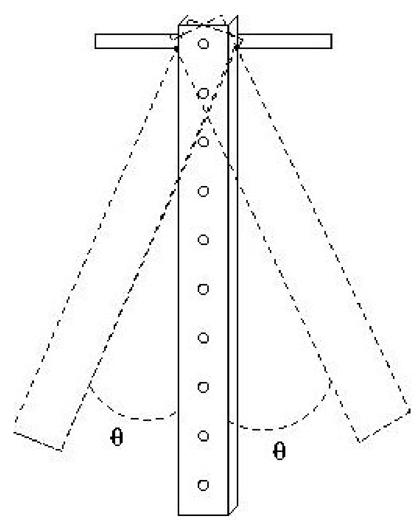


Fig.1 Bar Pendulum

Experimental Set-Up

In this experiment the rigid body consists of a rectangular mild steel bar with a series of holes drilled at regular interval to facilitate the suspension at various points along its length (see Fig.1). The steel bar can be made to rest on screw type knife-edge fixed on the wall to ensure the oscillations in a vertical plane freely. The oscillations can be monitored accurately using a telescope. The radius of gyration for this bar is

$$k^2 = \frac{l^2 + b^2}{12} \tag{5}$$

where l & b are the length & breath of the bar respectively.

Experimental Procedure:

1. Determine the center of mass (CM) by balancing the bar on a knife-edge. Measurement of d is made from this point to the point of suspension for each hole.

2. Suspend the bar by means of knife-edge.

3. Focus the telescope on to the marker marked on the pendulum. There should not be any parallax between the image of the marker and the cross wire in the eyepiece of the telescope.

4. Measure the time for 10 to 20 oscillations for different d (only on one side of CM). Repeat each observation several times.

Plot T Vs d. Calculate k and g from this graph.

Plot T^2d Vs d^2. Using linear regression technique fit the data and determines k and g from it.

Estimate maximum possible error in g.

Experiment 3

Bar Pendulum

Observations and Results

Least count of the measuring scale used = ………………….
Least count of the stop watch used = ………………….

Table I

S. No.	Distance from CM of axis (d) in cm	No. of oscillations (n)	Time period for n oscillations (Tn)	Time period (T) for 1 oscillation (Tn/n)	T^2d	d^2
1 (i)						
(ii)						
(iii)						
2 (i)						
(ii)						
(iii)						
3						
4						
5						
6						
7						
8						
9						

Calculation:

T_{min} from the graph =….at d=……

At T_{min} , d=k=…

$T_{min}=2\pi\sqrt{\dfrac{2\boldsymbol{k}}{\boldsymbol{g}}}$, so, g =…….

From the plot of T^2d vs. d^2 , find the slope and intercept from linear regression.

From the Slope $(4\pi^2/g)$, g can be calculated and from the intercept $[(4\pi^2/g)k^2]$, k can be calculated.

k can be calculated using the formula $\left(\dfrac{\boldsymbol{l}^2+\boldsymbol{b}^2}{12}\right)^{1/2}$ and compared with the value derived from the graph. Why are the two k values different?

Results:

'g' value from T vs. d plot is ……
'g' value from T^2d vs. d^2 plot is …….
Average value of 'g' = …..

(Two graph papers required).

References:

1. Haliday, Resnick and Walker, "Fundamentals of Physics", 6th Ed. (John Wiley, Singapore, 2001), Chap. 16.

Experiment No. 4

Rotational Inertia of a Rigid Body

Apparatus

Torsional pendulum, support for hanging the pendulum, regular circular body, irregular body, stop clock.

Objective:

To measure the rotational inertia of an object by dynamic method.

Theory

The equation of motion for small undamped rotational oscillations is

$$I\frac{d^2\theta}{dt^2} + C\theta = 0 \qquad (1)$$

Where I is the rotational inertia of the body about the chosen axis, θ is the angular displacement and C is the restoring (controlling) torque per unit angular displacement. This controlling torque is provided by the elastic rigidity of the wire with which the rigid body is suspended. For a wire of radius r, length l and rigidity modulus G, $C = G\frac{\pi r^4}{2l}$

(2)

Equation (1) represents a simple harmonic motion with angular frequency ω given by

$$\omega = \sqrt{\frac{C}{I}}$$

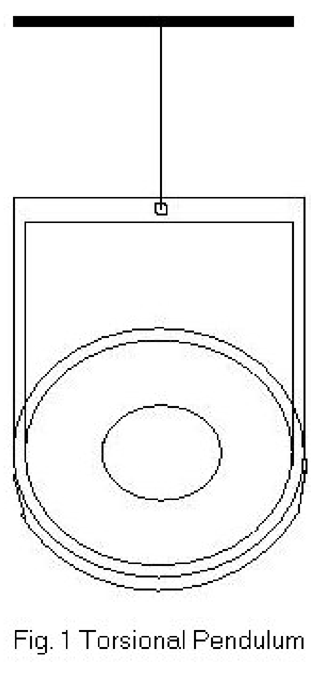


Fig. 1 Torsional Pendulum

And time period of oscillations

$$T = 2\pi\sqrt{\frac{I}{C}} \qquad (3)$$

In this experiment the time period (T_O) of the bare oscillating system is measured first and then with a regular body added to it. Since the rational inertia of regular body can be calculated from its dimensions and mass, we could use equation (3) in the two cases as follows :

For the bare system

$$T_0 = 2\pi\sqrt{\frac{I_0}{C}} \qquad (4)$$

Where I_0 is the moment of inertia of the bare system. With the regular body added, the time period would become

$$T_1 = 2\pi\sqrt{\frac{I_0 + K}{C}} \qquad (5)$$

Where K is the rotational inertia of the regular body.

One can solve equations (4) and (5) to get I_0 and C using the two measured time periods T_0 and T_1

If the given irregular body replaces the regular body then equation (5) gets modified to

$$T_X = 2\pi\sqrt{\frac{I_0 + X}{C}} \qquad (6)$$

Where X is the rotational inertia of the irregular rigid body . Since I and C are known, X can be calculated from equation (6).

Experimental Procedure

1. First ensure that the plate of the oscillating system is horizontal. You may have to adjust the leveling ring for this purpose.

2. Measure the frequency of oscillations of the system by timing about 30 oscillations or so. You may repeat the measurements a number of times to get a good mean value for the time period T_0. **Formulae used are applicable only for small oscillations.**

3. Place the regular body at the center of the plate and measure the frequency of oscillations again, by timing the number of oscillations as before for measuring the time period T_1.

4. Replace the regular body by the given object (irregular body) and measure the time period of oscillation T_x..

Observation Table

S. NO	System	Number of oscillations	Time for 30 oscillations (sec)	Time Period (sec)	Average Time period (sec)
1.	Bare system	(Repeat several times)			$T_0 =$
2.	With Reg.body	(Repeat Several times)			$T_{1=}$
3.	With Irreg. body	(Repeat Several times)			$T_{X=}$

Reference: Haliday, Resnick and Walker, "Fundamentals of Physics", 6th Ed. (John Wiley, Singapore, 2001), Chap. 11.

Experiment 5
Velocity of sound

Apparatus:

Audio frequency generator, speaker, microphone, Cathode Ray Oscilloscope (CRO), meter scale, large board (or wall), Thermometer (0-100^{0}C)

Purpose of experiment:

i) To determine the Velocity of Sound

ii) To understand the operation of a CRO

Basic methodology:

Sound waves produced by an audio frequency generator are made to reflect off a large reflecting board forming standing waves. A microphone connected to a CRO serves to measure the amplitude of the sound. The wavelength of sound waves is obtained from the positions of the nodes.

I. Introduction:

I.1. Standing waves are produced when two progressive sinusoidal waves of the same amplitude and wavelength interfere with each other. Consider two traveling waves traveling along the positive and negative x directions respectively

$$y_1(x,t) = A\sin(kx-\omega t) \qquad \text{------------------------- (1)}$$

$$y_2(x,t) = A\sin(kx+\omega t) \qquad \text{------------------------- (2)}$$

where A is the amplitude of the waves, $k = 2\pi\ \lambda$ is the wave number and $\omega = 2\ \pi\ f$ is the angular frequency. The quantity y(x,t) is the displacement of the medium at the point x and time t. When the two waves are made to interfere then by the principle of superposition, the net displacement is the sum of the individual displacements. Thus,

$$y(x,t) = y_1(x,t) + y_2(x,t) = A\sin(kx-\omega t) + A\sin(kx+\omega t)$$

$$\Rightarrow \quad y(x,t) = (2A\sin kx)\cos\omega t \qquad \text{--------------------------------- (3)}$$

The resulting displacement, eq(3) , represents a wave of frequency ω, and an amplitude, 2Asin kx , which varies with the position x. The amplitude is zero for values of kx that gives sin kx = 0 . These values are

$$kx = n\pi \text{ for } n = 0,1,2,3\ldots\ldots\ldots\ldots$$

Now $k = 2\ \pi / \lambda$. Therefore,

$$x = \frac{n\pi}{2}, n = 0,1,2,3......... \qquad \text{----------------------- (4)}$$

represents the positions of zero amplitude .These points are called nodes .Note that adjacent nodes are separated by $\frac{\lambda}{2}$, half of a wavelength.

The amplitude of the standing wave has a maximum value of 2A, which occurs for values of 'kx' that give $|\sin kx| = 0$. These values are

$$kx = (n + \frac{1}{2})\pi, n = 0,1,2,3.......... \qquad \text{------------------------} \textbf{(5)}$$

The positions of maximum amplitude are called *antinodes* of the standing wave.The antinodes are separated by $\frac{\lambda}{2}$ and are located half way between pairs of nodes. Now, a sound wave is a longitudinal wave representing displacement of particles in the medium and the resulting pressure variations. Traveling sound waves can also be taken to be represented by eqs. (1) and (2) with y(x,t) denoting the longitudinal displacements of air particles. The velocity of the sound wave will be given by

$$v = \omega / k = f \lambda \qquad \text{----------------------------------} \textbf{(6)}$$

In this experiment standing waves of sound are formed in air. The distance between successive nodes or antinodes is $\lambda /2$. By measuring the distance between the nodes, the wavelength can be determined and hence the velocity v of sound (knowing the frequency f). The apparatus of the experiment includes a cathode ray oscilloscope (CRO). One of the aims of the experiments is to provide a familiarity with the use of a CRO. The main features and controls of a CRO are described in the appendix to this experiment.

II. Setup and Procedure

Fig 1 shows the basic setup of the apparatus.

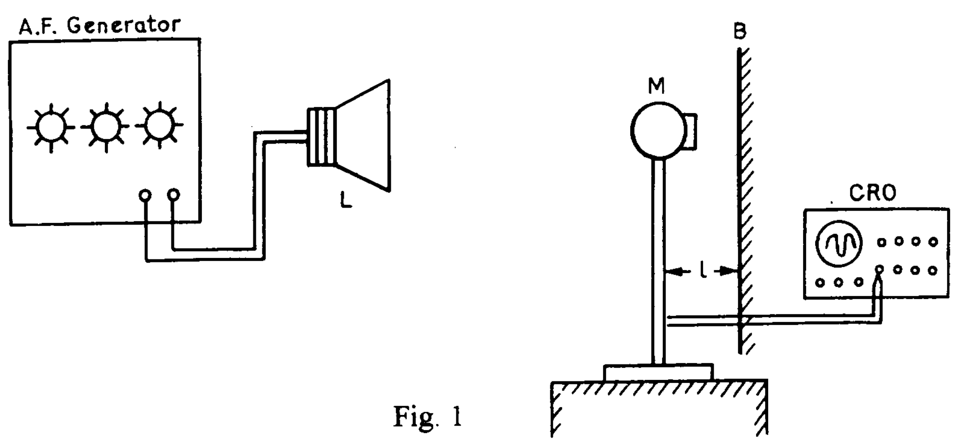


Fig. 1

PART A

Connect the audio frequency generator to the loudspeaker (L) and adjust the controls of the generator so that the speaker produces a sound signal in the frequency range I - 10 kHz. Place the loud speaker facing a large board B (or a wall) at a distance of about one meter.

Connect the small microphone (M) mounted on the bench. Connect the signal from the microphone to the y-channel of the CRT.

Select a proper scale for the horizontal time base to observe a stationary sinusoidal trace on the screen of the CRT. Adjust the vertical and horizontal positions so that the trace is symmetrically positioned on the screen. Observe that the amplitude of the trace changes as the position of the microphone is varied along the bench. Measure the period of signal by reading the number of horizontal divisions separating the minima of the signal on the CRO screen. From the chosen scale for the time base determine the time interval between successive minima of the trace and hence calculate the frequency of the signal and compare with the frequency generated by the audio generator.

Next place the microphone close to the wall and move it away from the wall. Note down the positions of the nodes, i.e. where the amplitude of signal on the CRT screen becomes minimum. Note down the positions of at least five successive nodes. Repeat this measurement for three different frequencies.

PART A

Set the Trigger source for the oscilloscope to external Trigger. Connect the output of the speaker to the X input of the scope.

Observe the Lissajous pattern produced on the screen. Move the microphone along the bench and observe different Lissajous patterns. Sketch the observed patterns for the cases when the phase difference between X and Y signal are 0^0, 90^0, 180^0, 270^0.

(Note: due to small amplitude of the signals the observed pattern may be small in size. Also due to attenuation of the reflected signals there can be distortion of the pattern).

Select (say) the straight-line pattern for O' or 180' phase difference. Starting from the position nearest to the loudspeaker move the microphone outwards towards the wall and note the positions of where the selected pattern repeats. The distance between two successive such positions corresponds to the wavelength of the sound wave.

Precautions:

1. *The microphone should be moved along the axis of the loudspeaker.*
2. *It is advisable to measure the position of nodes rather than antinodes*
3. *To lower error in the velocity determination the position of the nodes should be accurately determined.*
4. *The intensity of the CRO spot / pattern should be set LOW especially when the spot is stationary to avoid damage to the fluorescent screen*
5. *Learn the functions of the various control knobs of the CRO before operating the CRO.*

III. Exercises and Viva Questions:

1. What is a traveling wave? Write down equations representing waves traveling along +ve and -ve x directions.
2. What is a standing wave? Explain by superposing appropriate traveling waves.
3. What are nodes and antinodes? Draw a rough diagram depicting the standing wave formed in the experiment. Is the point at the reflection board a node or an antinode?
4. On what factors does the velocity of sound depend? What is the effect of temperature, pressure and humidity on the velocity of sound?

5. What are Lissajous figures? Explain by construction how Lissajous patterns are produced when two perpendicular oscillations of phase differences O^0, 90^0, 180^0, 270^0 are superposed.

6. List the different sub-systems of a CRO and explain their operation and function.

7. Explain how a CRO can be used for voltage, frequency and phase measurements? How can a CRO be used for current measurement?

8. A periodic signal of 400Hz is to be displayed so that 4 complete cycles appear on the oscilloscope screen, which has 10 horizontal divisions. To what settings should the Trigger source and sweep Time / div be set to allow this pattern to be displayed?

9. Explain what triggering, internal and external triggering mean.

10. List the possible sources of error in this experiment and quantitatively estimate

References:

1. **"**Fundamentals of Physics", D.Halliday, R.Resnick and J.Walker, 6th edition, John-Wiley & sons, New York.

2. "Physics", M.Alonso and E.J.Finn, Addison-Wiley, 1942.

Appendix: Cathode Ray Oscilloscope (CRO)

A cathode ray oscilloscope (CRO) is a convenient and versatile instrument to display and measure analog electrical signals. The basic unit of a CRO is a cathode ray tube (CRT). The CRO displays the signal as a voltage variation versus time graph on the CRT screen. By properly interpreting the characteristics of the display the CRT can also be used to indicate current, time, frequency and phase difference.

The basic subsystems of CRO are:

1. Display subsystem (CRT,)
2. Vertical deflection subsystem
3. Horizontal deflection subsystem
4. Power Supplies
5. Calibration circuits

Fig.1 shows a schematic diagram block diagram of how the subsystems are interconnected to produce the observed signal.

produce the observed signal.

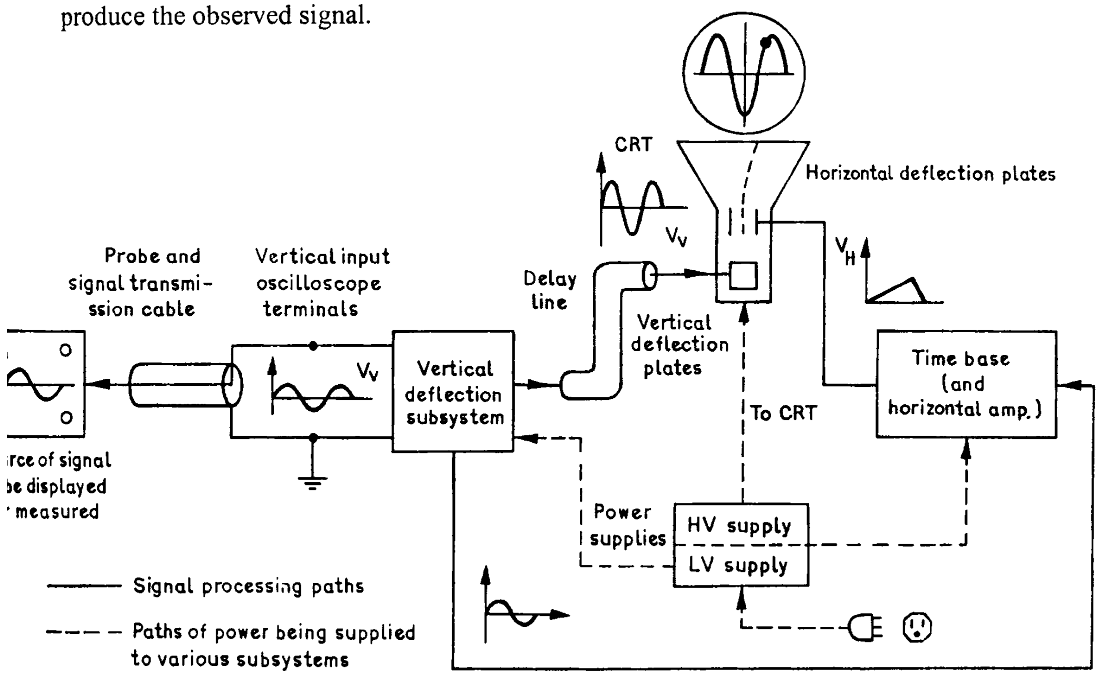


Fig. 1

The Signal is sensed at its source by the oscilloscope probe. The signal voltage is then transmitted to the oscilloscope along a coaxial cable and fed to the vertical display subsystem. After suitable amplification, the input signal is applied to the vertical deflection plates of the CRT. This causes the electrons emitted by the electron gun in the CRT to deflect vertically in proportion to the amplitude of input voltage.

There is a simultaneous deflection of the electron produced by the horizontal deflection subsystem. The amplified input signal is also fed to the horizontal deflection subsystem. In order to produce a Y-t display a voltage that causes the horizontal position of the beam to be proportional to time must be applied to the

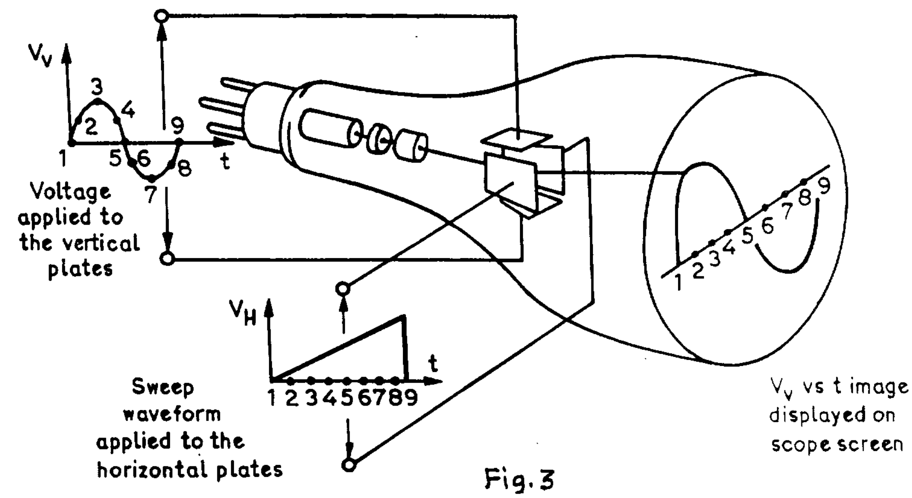


Fig. 3

horizontal deflection plates. The horizontal voltage called the sweep waveform is generally of a saw tooth form. Fig. 3 shows has the time variation of the input signal is displayed with help of the sweep waveform.

The synchronization of the input signal with the sweep wave form is carried out by the time base circuitry. A triggering signal (which could be the input signal or an external signal) is fed to a pulse generator. The emitted pulses are fed to a sweep generator, which produces a series of sweep waveforms.

Controls on the CRO front panel:

A. General

Intensity: Controls the intensity of the spot on the screen by controlling the number of electrons allowed to pass to the screen

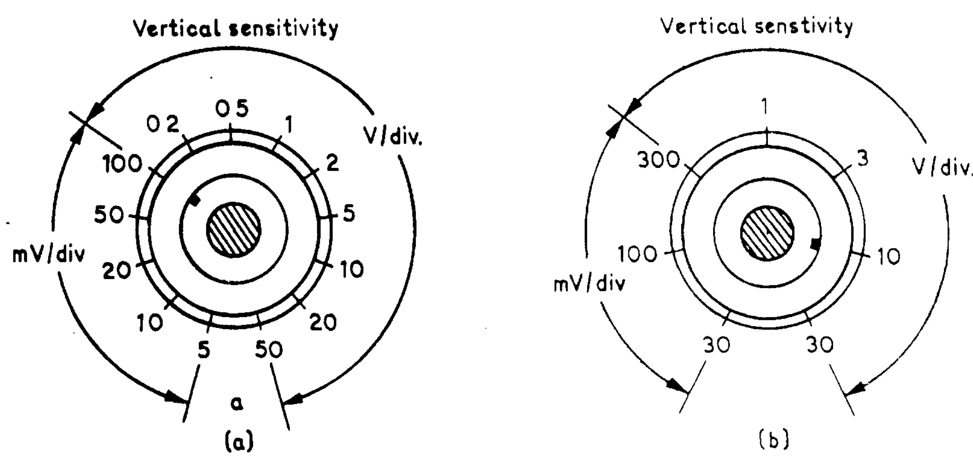
Focus: Controls the focusing of the electron beam.

X Shift / Y Shift: Changes the deflection voltages by a constant amount to shift the signal vertically or horizontally.

B. Vertical Deflections Subsystem

Vertical sensitivity: Amplifier for the vertical deflection subsystem calibrated in ten-ns of sensitivity. The input voltage can be determined from the deflection of the signal. For eg., if the vertical sensitivity is set at 50 mV/div and the vertical deflection is 4 div, then the input voltage is 50 x 4 = 200 mV.

Var (Vldir): Vernier control for continuous vertical sensitivity.



C. Horizontal Deflection Subsystem

Sweep Time (Time/dir):

Controls the sweep time for the spot to move horizontally across one division of the screen when the triggered sweep mode is used.

Var (Time/div):

Vernier control for continuous change of sweep time.

Trigger:

Selects the source of the trigger signal, which produces the sweep waveform.

Internal Trigger:

The output of the vertical amplifier is used to trigger the sweep waveform.

External Trigger:

An external signal must be applied to the X inputs to trigger the sweep waveform.

Sweep Magnifier:

Decreases the time per division of the sweep waveform.

***Trigger Level**:*

Selects amplitude point on trigger signal that causes sweep to start.

Trigger Mod:

AUTO provides normal triggering and provides baseline in absence of trigger signal. NORM
permits normal triggering but no sweep in absence of triggering. TV provides triggering on TV field or TV line**.**

References:

1. "Student Reference Manual for Electronic Instrumentation", S.E.Wolf and R.F.M.Smith, PHI, New Delhi, 1990.
2. "Basic Electronic Instrument Handbook", C.F.Coombs, Mc Graw Hill Book Co., 1972.

Observations and Results

PART A

1. Room Temperature = ________________________ ^0C
2. Frequency of Audio signal = ________________________
3. Time/div scale setting = ________________________
4. Calculated frequency from CRO screen = ________________

Table 1 : Position of Nodes

S.No	Position of microphone at nodes(cm) Frequency			Distance between successive nodes for the following frequencies(in cm)		
	f_1=______kHz	f_2=_____kHz	f_3=_____kHz	f_1=______kHz	f_1=______kHz	f_1=______kHz
1						
2						
3						
4						
5						

Calculations:

	f_1 = ____ kHz	f_2 = _____kHz	f_3 = _______kHz
Average $\lambda/2$ (cm)			
Average λ (cm)			
Velocity of Sound , $v = f\lambda$			

Results:

The velocity of sound in air at room temperature ___________ ^{0} C is

v = ___________________________________ m/ sec.

Estimate the error in your determination of velocity of sound:

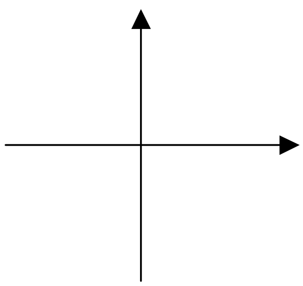
$V_{Emp}(T) = V_0 \sqrt{T}$; V_0 = at 20^{0} or NTP

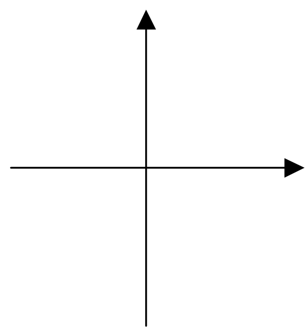
Then calculate $\dfrac{|\Delta V|}{V_{EMP}}$

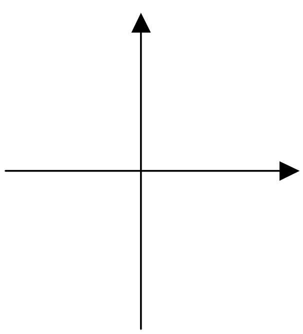
$|\Delta V| = V_{EMP} \sim V_{tmp}$

PART B

1. Sketch Lissajous pattern observed on the CRO screen for the phase differences of 0^{0}, 90^{0}, 180^{0}, 270^{0} between X and Y signals.







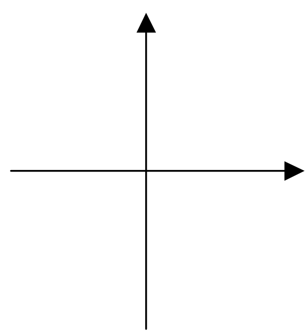


Table 2

Frequency of audio signal = ………………………………………….
Phase difference for pattern selected = ……………………………….

S. No.	Position of microphone	Difference between successive position λ (cm)
1		
2		
3		
4		
5		

Average λ= ______________________________ cm

Result:

The velocity of sound v=f λ = ____________________________ m/s

Do error analysis same as in part A.

Experiment 6

Radiation from a Black Body: Stefan-Boltzmann Law

Apparatus

Blackened hemisphere (metal), heating coil, blackened silver disk, thermocouple, power supply, stop clock etc.

Objective

To determine the Stefan–Boltzmann constant σ by studying the radiation received from a black body radiator.

Theory

The total radiation from black body is given by Stefan-Boltzmann relation

$$R = \sigma T^4 \qquad \text{(per cm}^2\text{ per sec)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

where R is the radiant energy per unit area per unit time and T is the absolute temperature of the body. This relation was empirically deduced by Josef Stefan from the experimental results of John Tyndall and was derived by Ludwig Boltzmann from theoretical considerations based on thermodynamics.

Consider a black body radiator at temperature T_1 and a metal disc at temperature T_2 as the receiver of the radiation (fig 1.). If R_1 and R_2 be the radiation absorbed and emitted by the receiving metal disc respectively, then the energy gained per second by the disc is $(R_1 - R_2)A$; where A is the area of cross-section of the disc. If *m* and *s* are the mass and specific heat of the disc, then

$$ms\frac{dT_2}{dt} = \frac{(R_1 - R_2)}{J}A = \frac{\sigma A}{J}\left(T_1^4 - T_2^4\right)$$

$$\Rightarrow \quad \sigma = \frac{Jms}{A\left(T_1^4 - T_2^4\right)}\frac{dT_2}{dt} \qquad (2)$$

where dT_2/dt is the rate of change of temperature of the disc. J=Joules' equivalent (4.2×10^7 ergs/calorie).

Experimental Setup

The experimental Setup (Fig.1) consists of a blackened hollow hemisphere which could be heated to a uniform temperature (T_1) by passing electric current through a nichrome heating element wounded over it.

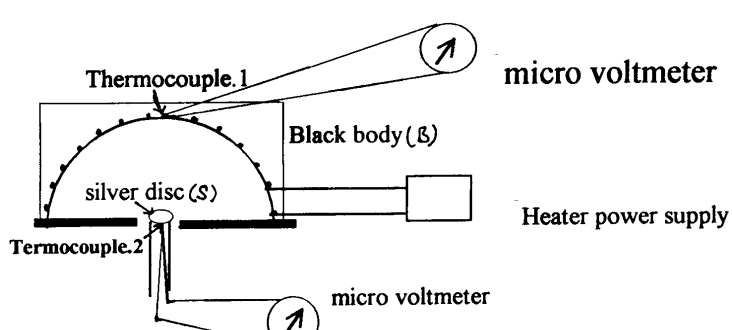


Fig. 1

The black body could be maintained at any desired constant temperature up to about 200^0 C by passing appropriate current through heating coil. A copper–constantan thermocouple 1 connected to outer surface of B is used to ensure that temperature of the body is constant before starting the experiment. A blackened silver disc S serving as the receiver is inserted into the hole in B. The thermocouple 2 connected to the disc is used to measure its temperature.

Procedure:

1. Heat B to a uniform temperature (usually heating will be started before you come to the lab). Ensure that the temperature of the black body is constant by monitoring the thermo emf developed by thermocouple 1 for few minutes (ignore small fluctuations in micro voltmeter display).

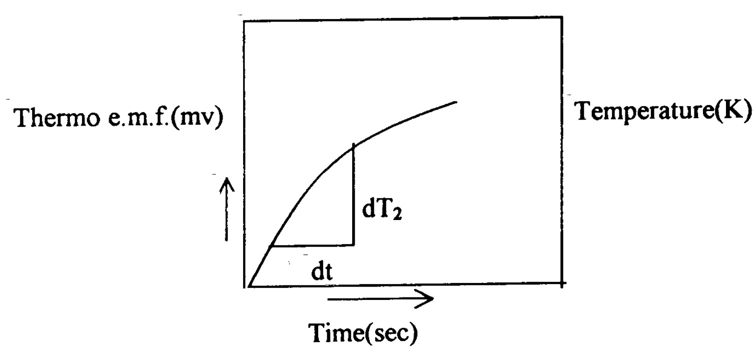
2. Insert a thermometer through the hole provided for the disc S **carefully** and measure the temperature T_1 of the black body.

3. Replace thermometer with the silver disc carefully and mount it properly (make sure that disc is at room temperature before inserting).

4. Record the thermo emf of thermocouple 2 developed as a function of time (say at 10 sec interval).

5. Note down the mass and diameter of the disc.

6. Convert the thermo e.m.f. to temperature (T_2) by using the calibration chart for it (will be supplied to you).



7. Plot T_2 as function of time, obtain dT_2/dt from the data and calculate the value of σ.

(Specific heat of the silver disc at room temperature s= $0.235 Jg^{-1}K^{-1}$)

Observations:

Mass of the disc:

Diameter of the disc:

Temperature of the black body (T_1)= …

Temperature of the disc (T_2)=….

Table for recording thermo e.m.f. as a function of time:

Sl. No.	Time (sec)	Thermo e.m.f. (mv)	Temperature (K)
1	10		
2	20		
3	30		
4	40		
5	50		
6	60		
7	70		
…	80		
…	90		
…	….		

Plot T vs. time and find the slope and use eqn. (2) to calculate σ.

Result:

Measured value of σ = …….

(Two graph papers required).

References:

1. M. W. Zemansky and R. H. Dittman, "Heat and Thermodynamics, an intermediate textbook" (MGH, 6th ed, 1981), Chap. 4.
2. B. L. Worshnop and H. T. Flint, "Advanced Practical Physics for Students" (Khosla Publishing House, 1991).

Experiment 7

Melting point of Solids

Apparatus
Electric oven/heater, glass tube, thermometer, thermistor, voltmeter, unknown solid for which melting point is to be found out.

Objective

To calibrate a thermistor using a thermometer and using the calibrated thermistor as temperature sensor find the melting point of a given chemical compound.

Theory:

Thermistors (the name originated from thermal resistors) are basically semiconductor devices with a characteristic negative temperature co-efficient of resistance. The temperature dependent resistance of the thermistor is exploited in its application as a temperature sensor. The sensitivity (>6% change in resistance per ^{0}C rise in temperature) and its rugged construction made it suitable for precision temperature measurement in the temperature range –100°C to 300°C. Since thermistors are made up of a mixture of metallic oxides such as Mn,Ni,Co,Fe,U etc., their resistance could be tailored between 0.5 Ω to 75 MΩ. They can also be made in varying sizes(beads as small as 0.15mm dia.) and shapes. Thermally cycled thermistors give an extremely reproducible and reliable resistance value over the specified dependence of the resistance of a typical thermistor.

Melting point of a solid:
In a solid, the relative distance between two atoms is fixed and atoms occupy equilibrium positions. These atoms oscillate about their equilibrium positions. When the substance is heated, the energy is partially used to increase the amplitude of atomic oscillations. This results in thermal expansion of solid.

At sufficiently high temperature the solid melts, i.e. the atoms leave their equilibrium position overcoming the binding energy and wander great distances through the resulting liquid. However, even just below the melting point the atoms are in the vicinity of their equilibrium positions. Hence substance must be supplied an extra energy required for melting process. This extra energy is called latent heat. If energy is supplied at uniform rate, the sample remains steady at melting temperature until it absorbs the latent energy. The typical plot of temperature variations of a solid across its melting point, with time is shown in fig.1.

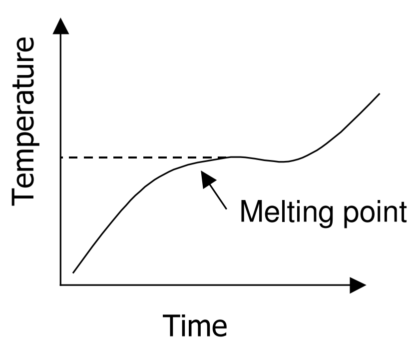


Fig. 1

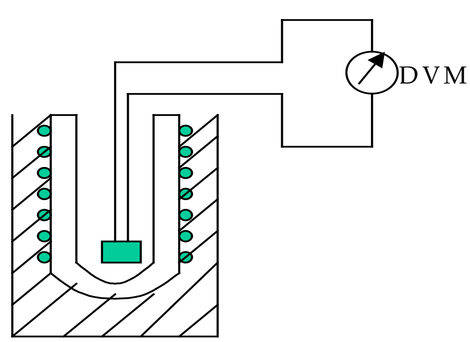


Fig. 2

Experimental Set up:

An electrical oven has been designed for this experiment. A heating element is wound a thin hard glass test tube. This test tube is thermally insulated from outer wall of the oven. This oven can heat the substances up to 110°C by passing appropriate amount of current. The thermistor resistance is measured using a Digital voltmeter (DVM). The schematic of the setup is shown in Fig. 2.

Procedure:

The thermistor and the thermometer put together in the oven and heat the oven by passing appropriate current through it. Measure the resistance of the thermistor from room temperature to about 80°C. Plot the graph for resistance Vs temperature.(Switch off the power supply immediately just after taking the readings). Now take the supplied chemical in a test tube with the thermistor and put it inside the oven (Make sure that initially inside of the oven is around the room temperature). Heat the oven and measure the resistance of the thermistor in a regular time interval beyond the melting point(as you know during melting resistance of the thermistor will be remain almost constant)

Analysis:

Plot the resistance Versus time. Calculate the melting point of the given sample using the characteristics shown in fig. 1.

Observations:

Calibration of thermistor :

S. No.	Temperature (^{o}C)	Resistance (Ω)
1	RT (25)	
2	30	
3	35	
4	40	
5	45	
6	50	
7	55	
…	…	
….	…	
….	…	

S. No.	Time (sec)	Resistance (Ω)
1	0	
2	10	
3	20	
4	30	
5	40	
6	50	
7	60	
…	…	
….	…	
….	…	

Analysis:
Plot two graphs and find the melting point (temperature) from the flat region of the 2nd graph graph.

Results:

Melting point of the given solid is = …… ^{o}C

(Two graph papers required).

Experiment 8

Measurement of $\dfrac{e}{m}$ by Thomson's bar magnet method

Apparatus:
Cathode ray tube (CRT) with power supply unit, one pair of bar magnets, high resistance voltmeter, magnetometer, and stopwatch.

Purpose of the experiment:

To measure the specific charge, i.e. charge to mass $\left(\dfrac{e}{m}\right)$ ratio, of an electron using Thomson's bar magnet method.

Basic Methodology:
Electrons in a CRT are deflected in the vertical direction by applying a potential between the vertical deflection plates of the CRT. A magnetic field perpendicular to the deflecting electric field is produced using a pair of the bar magnets. The position of the magnets is adjusted so as to cancel the deflection of the electrons. The knowledge of the deflecting potential and the magnetic field of the bar magnets leads to a calculation of the specific charge.

I. Introduction

We have learnt that the electron has a negative charge whose magnitude e equals $1.6\text{x}10^{-19}$ Coulomb and mass (m) equal to $9.1 \text{ x } 10^{-31}$ Kg. Millikan's Oil Drop method enables us to measure the electron charge but the mass of the electron can not be measured directly. It is calculated by measuring the value of e/m. The aim of this experiment is to determine value of e/m by Thomson's method. This involves the motion of an electron in a cathode ray tube (CRT).

A simplified form of a cathode ray tube is shown in Fig. 1. The electrons are emitted from the cathode and accelerated towards the anode by an electric field. A hole in the accelerating anode allows the electrons to pass out of the electron gun and between the two sets of deflection plates. The metallic coating inside the tube shields the right end free of external electric fields and conducts away the electrons after they strike the fluorescent screen where they form a luminous spot.

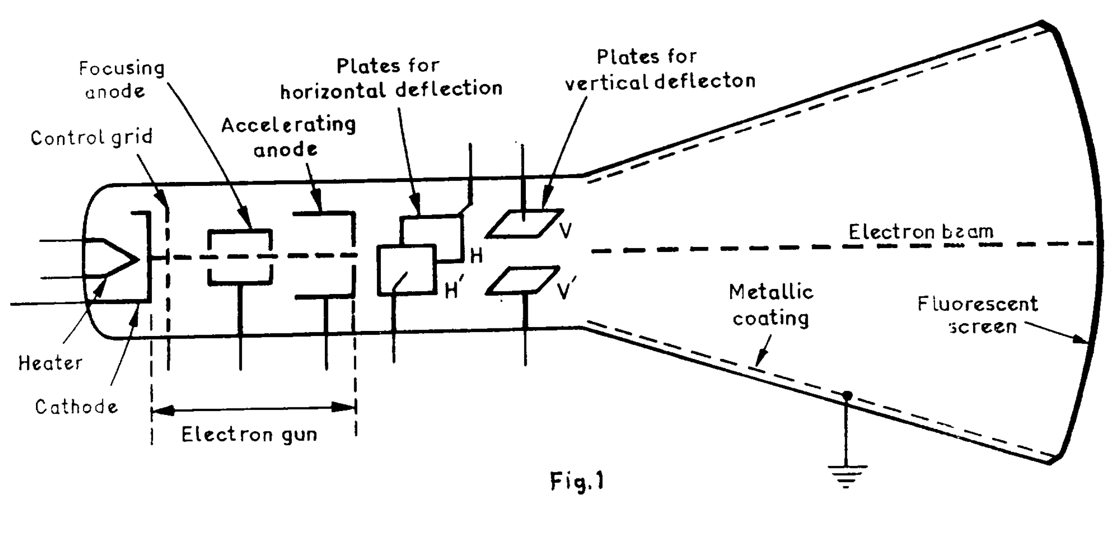


Fig.1

I.2 This experiment can be divided into the following parts:

1. The electric field (E) is applied alone. This produces a deflection of the electron beam.
2. A magnetic field is simultaneously applied along the electric field so that the deflection produced by the electric field is exactly counter-balanced by that produced by the magnetic field. As a result the spot made by the electron on the fluorescent screen returns back to the central position.

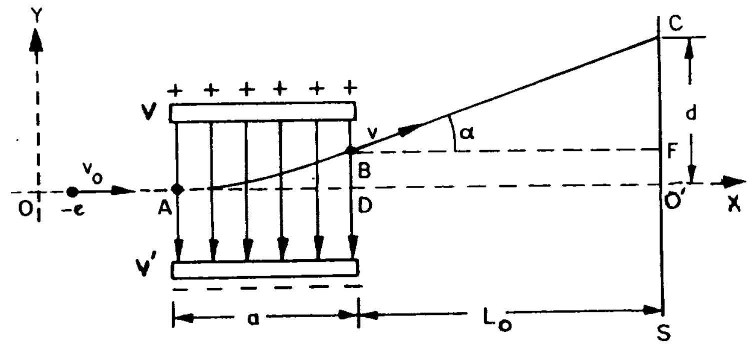


Fig. 2

Let us consider an electron moving in the direction of magnetic meridian (say X-axis) with the velocity v_0 m/s after passing through the accelerating anode. Under the action of the electrostatic field E = V/s (s being the vertical distance between the plates VV' and V the deflecting voltage)each electron ,as it passes between the plates , is acted upon by a perpendicular force eE. As a result the electron moves along a parabolic path AB(fig 2).The equation of motion is

$$m\left(\frac{d^2 y}{dt^2}\right) = eE \qquad \textbf{-------------------------------- (1)}$$

which, upon integrating once with respect to time, gives

$$v_0\left(\frac{dy}{dt}\right) = \left(\frac{eE}{m}\right)t \qquad \textbf{------------------------------------ (2)}$$

where v_0 = dx / dt is the constant horizontal velocity .Here we also used the initial condition dy/dx = 0 at point A time t=0. At any point distant x(=v_0 t) from point A in the field between the plates VV', eq(2) gives

$$\frac{dy}{dx} = \left(\frac{eE}{mv_0^2}\right)x \qquad \textbf{------------------------------------- (3)}$$

On leaving the electrostatic field at point B (i.e. x=a), the electron moves along the tangential path BC with it's velocity making an angle α with the horizontal. Clearly,

$$\tan\alpha = \tan FBC = \left(\frac{dy}{dx}\right)_{\text{at point B}} = \left(\frac{eE}{mv_0^2}\right)a \qquad \textbf{------------------------- (4)}$$

= Tangent to the curve AB at point B

The electron finally strikes the screen at the point C (fig 2). The total vertical deflection of the electron

$$y = CF + FO'$$

Now

$$CF = BF \tan\alpha = L \tan\alpha = \frac{eEaL}{mv_0^2} \qquad \textbf{--------------------------- (5)}$$

On the other hand, by eq (3), we have

$$BD = \int\left(\frac{eEx}{mv_0^2}\right)dx = \frac{eEa^2}{2mv_0^2} \qquad \textbf{------------------------------- (6)}$$

Therefore the total displacement (y) in the spot position on the screen S due to the application of electric field between the plates VV' is

$$y = CF + FO' = CF + BD$$

$$y = \frac{eEa}{mv_0^2}\left(\frac{a}{2}+L\right) \qquad \text{-----------------------------------} \textbf{(7)}$$

Thus

$$\frac{e}{m}=\frac{v_0^2\, y}{Ea\left(\frac{a}{2}+L\right)} \qquad \text{-----------------------------------} \textbf{(8)}$$

Hence, if the velocity of electron along the X-axis (v_0) is known, the value of (e/m) can be calculated.

I.3 Let B be the magnetic field produced by the two bar magnets placed symmetrically on either side of the cathode ray tube at a distance d from it. The magnetic field of the bar magnets will be in the east- west direction. The magnetic force in the electron is given by $\vec{F}=-e\left(\vec{v}\times\vec{B}\right)$. This step up a force Bev_0 on the moving electron along the Y-direction. As a result, the electrons path becomes circular, with radius of curvature r given by

$$\frac{mv_0^2}{r} = Bev_0 \qquad \text{-------------------------------------} \textbf{(9)}$$

When the force on the electron beam due to crossed electric field and magnetic field is equal and opposite, the electron beam will be un deflected.

For this we require

$$eE=ev_0 B \qquad \text{or} \qquad v_0=\frac{E}{B}$$

The above analysis assumes that the magnetic field B is uniform. However the magnetic field produced by the bar magnet is non-uniform. Fig.3 shows the arrangement of the magnets with respect to the CRT.

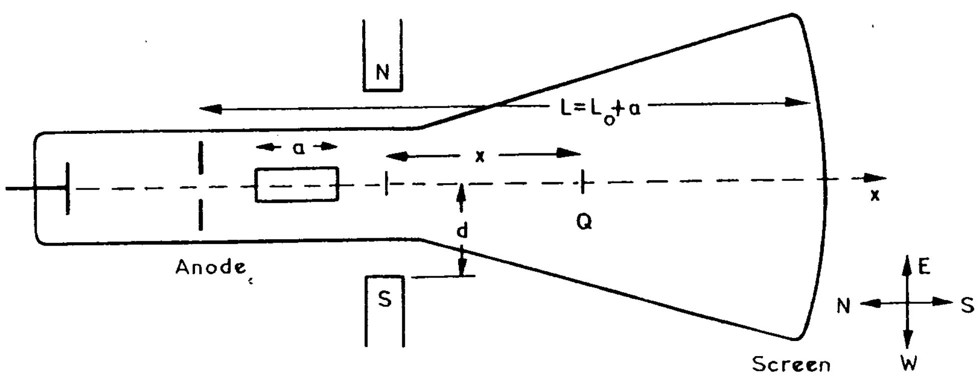


Fig.3

Note that the CRT is aligned along the magnetic meridian, i.e. S-N direction, which is the direction along which the horizontal component of the earth's magnetic field, B_E acts. Since B_E and the electron velocity are parallel, there is no deflection produced by the earth's magnetic field.

The magnetic field produced by the bar magnet along the path of the electrons will be a function B(x) of the position of the element and will act in the EW direction as shown in fig 3. The deflection, y, due to the magnetic force will be in the negative y-direction. To calculate the total deflection of the electron as it moves from A (anode aperture) to S (screen) we proceed as follows.

The radius of curvature r of the electron path y(x) in the presence of the magnetic field is related to the curvature of the path as

$$\frac{1}{r} = \frac{d^2 y}{dx^2}$$

Of course, the radius of curvature will also change with position since the magnetic field changes, i.e.

$$r = r(x) = \frac{m v_0}{e B_{(x)}} \qquad \text{by eq .(9).}$$

Thus,

$$\frac{d^2 y}{dx^2} = \frac{e B(x)}{m v_0} \qquad \textbf{-------------------------------- (10)}$$

which upon integrating gives,

$$y(x) = \int \left[\int \frac{e B(x)}{m v_0} dx \right] dx$$

The net displacement y at the position of the screen (i.e. $x = L_0 = L\text{-}a$) is then

$$y = \int_0^{L_0} \left[\int_0^x \frac{e B(x)}{m v_0} dx \right] dx = \frac{e I}{m v_0} \qquad \textbf{--------------------------- (11)}$$

where we have denoted the double integral of the magnetic field as

$$I = \int_0^{L_0} \left[\int_0^x B(x)\, dx \right] dx \qquad \textbf{----------------------------- (12)}$$

when the deflection due to the electric and magnetic field are the same then we can use eqs(7) &(11) and eliminate the unknown velocity v_0 to obtain

$$\frac{e}{m} = \frac{\left(\frac{a}{2} + L\right) a V y}{s I^2} \qquad \textbf{------------------------------ (13)}$$

I.4. Approximate evaluation of:

A calculation of the integral 'I' requires the knowledge of the magnetic field produced by the magnets along the path of the electron in the CRT. We now give an approximate calculation of I assuming that the magnets are very long compared to the length of the CRT (L_0). (See fig 3). The effect of the distant poles can be ignored. The field at the point Q, which will be in a direction normal to the x-axis, is

$$B(x) = \frac{(m + m')d}{(x^2 + d^2)^{3/2}} \qquad ,$$

here, m and m' are the pole strengths of the N and S poles . The maximum of the magnetic field, B_m occurs at x = 0.

$$B_m = \frac{(m + m')}{d^2}$$

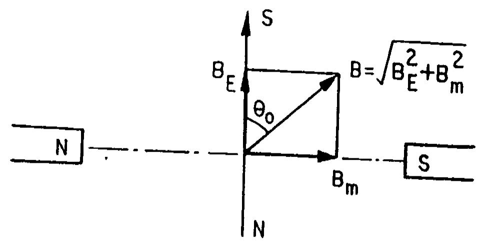
Thus, we can write,

$$B(x) = \frac{B_m d^3}{(x^2 + d^2)^{3/2}} \qquad \textbf{---------------------------- (14)}$$

The integral $I = \int_0^{L_0} dx \int_0^{x} dx\, B(x)$ can be evaluated to give,

$$I = B_m \left[d\sqrt{d^2 + L_0^2} - d^2 \right] \qquad \text{------------------------------- } \mathbf{(15)}$$

I.5. Determination of B_m:



The value of B_m is determined from the period of oscillation of the magnetometer needle. The magnetometer is placed at the center in place of CRT so that the magnets are at a distance of d from it (see fig4). The magnetometer needle aligns itself along the resultant magnetic field

fig 4

$B = \sqrt{B_E^2 + B_m^2}$ where B_E is the earth's magnetic field acting towards south .

A small disturbance of the needle about the equilibrium position causes it to oscillate. The angular frequency of small oscillations can be easily shown to be (Exercise 7) $\omega = \sqrt{\frac{\mu B}{I}}$, where μ is the magnetic moment of the needle and I it's moment of inertia, and hence the time period of small oscillations $T = 2\pi\sqrt{\frac{I}{\mu B}}$.

Now, the resultant magnetic field $B = \sqrt{B_E^2 + B_m^2} = B_m / \sin\theta_0$. Thus

$$B_m = \frac{4\pi^2 I}{\mu} \frac{\sin\theta_0}{T^2}$$

In the absence of the magnets $B=B_E$ (due to the earth's magnetic field) and the time period $T_0 = 2\pi\sqrt{\frac{I}{\mu B_E}}$ giving $\frac{4\pi^2 I}{\mu} = T_0^2 B_E$,

Thus,

$$B_m = \frac{T_0^2}{T^2} B_E \sin\theta_0 \qquad \text{------------------------------- } \mathbf{(16)}$$

With a determine of B_m the value of the eq(15) can be calculated and hence from eq(13) the value of (e/m).

II. Setup and Procedure:

PART A

1. Place the magnetometer on the wooden box enclosing the CRT. Rotate the dial so that 0^0-0^0 position is perpendicular to the length of the CRT. Next rotate the CRT with the magnetometer on it so that the magnetometer needle aligns along 0^0-0^0 position. In this position the CRT is aligned along the magnetic meridian (N-S position) while the scales attached perpendicular to the CRT (for magnetic mounting), are in E-W position.

2 Switch on the power supply and adjust the intensity and focus controls to obtain a fine spot on the CRT screen.
(Note: the position of the spot may not be at the center of the CRT screen. Note down

the initial position of the spot)

3. Choose a value of the deflection voltage and note down the deflection of the spot.
   (Note: the deflection has to be taken with respect to the initial spot position.)

4 Now extend the scales attached to the CRT and place identical bar magnets (as shown in Fig.3) and move the magnets symmetrically along the length of the scales until the spot deflection becomes zero (i.e. the spot returns to its initial position). Note the value d of the distance of the magnet poles from the center of the CRT.

5. Reverse the deflection voltage and (with magnets removed) note the deflection of the spot.

6. Place the magnets on the scale and find the value of d for which the spot returns to its

7. Repeat the above steps for three different spot positions
   (Note: The deflection voltage should not exceed 375 volts)

PART B

Determination of time period of oscillation of magnetometer needle:

1. Align the wooden arm on which the magnetometer is placed along the magnetic meridian and place the magnets along the scales in the EW direction at the same distance 'd' as in part A.
2. Note the equilibrium deflection $\theta_{0.}$
3. With a third magnet, slightly disturb the needle from its equilibrium position and measure the time period of oscillations T.
4. Now remove the magnets and let the needle come to equilibrium at 0^0-0^0 position.
5. Disturb the needle about to this equilibrium position and measure the time period T_0 of the oscillation.

Precautions:

1. The Cathode ray tube should be accurately placed with its longitudinal axis in the magnetic meridian.
2. The spot on the screen should allowed to remain at a given position on the screen for a long time.
3. There should not be any other disturbing magnetic field near the apparatus.
4. While taking the observations for time periods, the maximum angular displacement of the magnetic needle should not exceed 40-50 degrees.

III. Exercises and Viva Questions:

1. Study the working of a CRT. What is the typical value of accelerating voltage

used in a CRT? Estimate the velocity 'v_o' of the electron.

2. What will happen to the spot if a sinusoidally time varying voltage is applied to the deflecting plates $VV^{/}$ or $HH^{/}$? What will happen if such a voltage (of the same frequency) is applied simultaneously to the horizontal and vertical deflecting plates?

3. Draw a neat diagram showing the 3-dimensional orientations of vectors of the electron's horizontal velocity, the electric field, the magnetic field the electric force on the electron and the magnetic force as the electron moves in the CRT. Orient your diagram according to the experimental set-up.

4. If the deflecting voltage is switched off but the bar magnets kept in place, will there be a deflection of the spot? Describe qualitatively the motion of the electron in the CRT from aperture to screen.

5. Describe the motion of the electron in the CRT in the presence of the deflecting voltage magnetic fields of the magnets

6. What is the effect of earth's magnetic field on the electron motion? What would happen if the apparatus were rotated by 90^0 so that the CRT is along the EW direction?
7. Consider a dipole μ aligned with a magnetic field .If the dipole is given a small angular displacement, then it experiences a restoring torque 'τ' $=\mu B\sin\theta$, where 'θ' is the angle between the dipole and the magnetic field . Considering small displacements θ, show that the dipole will oscillate about the equilibrium with angular frequency $\sqrt{\dfrac{\mu B}{I}}$. Where 'I' is the moment of Inertia.

8. Recalculate the integral 'I' (eq 12) assuming that the magnetic field of the magnet is a constant $B=B_m$. Use this to calculate the specific charge "e/m". Does our approximate evolution of 'I' improve the evaluation of "e/m"?

9. What are the sources of error in this experiment?

10. How does your result compare with "e/m" measurement by Thomson's method ? Which experiment is more accurate?

References:

1. "Advance Practical Physics for Students", B.L.Worsnop and H.T.Flint, Mentheum London, 1942.

2. "Physics", M.Alonso and E.J.Finn, Addison-Wiley, 1942.

Experiment 8
Measurement of e/m by Thompson's bar magnet Method

Observations and Results

1. <u>Constant Values</u>

Length of plate, a = 2 cm
Distance to screen from plate, L = 16.0 cm
Distance between the plates, S = 0.4 cm
Horizontal component of earth's magnetic field $B_E = 3.53 \times 10^{-5}$ T .

PART A: Measurement of deflection y:

Initial position of spot, y_o = ____________________ cm (specify +ve or –ve)

Table 1

Applied Voltage V(volts)	Displaced position of spot y_1 (cm)		Displacement of spot $y = y_1 - y_o$		Mean Displacement y(cm)	Position of magnet d (cm)		Mean d (cm)
	Direct	Reverse	Direct	Reverse		Direct	Reverse	
1								
2								
3								

PART B Determination of Time period

Table 2(all time measurements are in seconds)

No. of Oscillations = ____________________

S.No	Without Magnet		With Magnet					
			d = ____ cm θ_o= _____ deg		d = ______ cm θ_o= _____ deg		d = ______ cm θ_o= _____ deg	
	Total time	T_o	Total time	T	Total time	T	Total time	T
	Mean T_o		Mean T					

Calculations:

Displacement	$B_m = \frac{T_o^2}{T^2} B_E \sin\theta_O$	$I = B_m \left[d\sqrt{d^2 + L_o^2} - d^2 \right]$	$\frac{e}{m} = \frac{\left(\frac{a}{2} + L\right) a V y}{s I^2}$
1			
2			
3			

Results:

Calculated value of specific charge of electron (e/m) = __________________ C/Kg.

Standard Value of (e/m) = _________________ C/Kg

% error in e/m = _________________.

Experiment 9

Measurement of "(e/m)" by helical coil method

Apparatus:
Cathode ray tube (CRT), CRT power supply, DC power supply (30V), solenoid, Rheostat, DC voltmeter, and connecting wires.

Purpose of experiment:
To measure the specific charge, i.e. .charge to mass ratio (e/m) of an electron.

Basic methodology:
Electrons are accelerated towards the screen of a CRT and also deflected by a transverse AC voltage. The CRT is placed in a magnetic field produced by a solenoid. The resulting motion of the electron is then helical .A measure of the pitch of the helix leads to a calculation of the e/m ratio .

Introduction

1.1 Electron are emitted at the cathode of a CRT and accelerated through an accelerating DC voltage V_a towards the screen. In addition a small transverse (AC) voltage acts across the $XX^{/}$ plates.. Once the electron leaves the plate region its velocity 'v 'is constant and makes angle θ with Z-axis. The component of it's velocity along Z-axis is $v_{||} = v \cos\theta \sim v$. When the AC deflecting velocity is switched on, different electrons receive varying velocity $v_{\perp}$ and hence a line gets formed on the CRT screen.

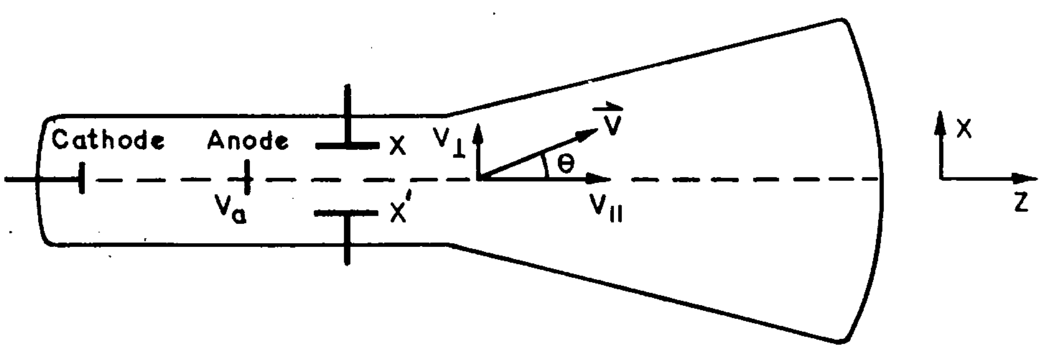


fig 1

I.2 When the CRT is placed along the axis of the solenoid then there is a magnetic field $B=\mu_o\ n\ I$ (along the axis of the solenoid) which acts on the electron. Here n=number of turns per unit length of the solenoid and I=current in the solenoid, length of the solenoid and I=current in the solenoid.

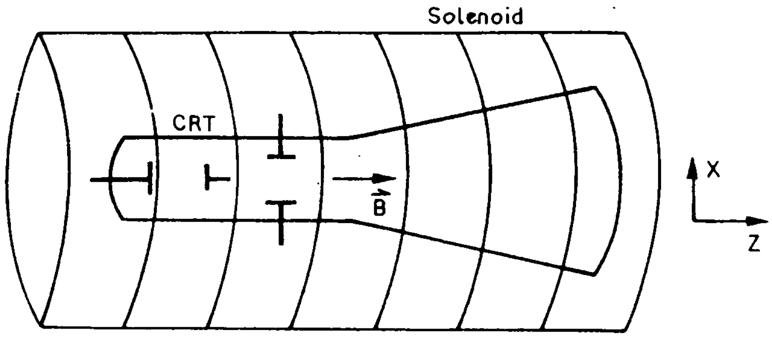


Fig 2

I.3 When the magnetic field is present the motion of the electron in the CRT is helical. This is seen as follows. Viewed along the Z-axis with the magnetic field coming out of the page, the magnetic field has the effect of making the electron move in a circular path (fig3). The centripetal force is

$$\frac{m v_\perp^2}{r} = e v_\perp B \qquad \text{--------} \ (1)$$

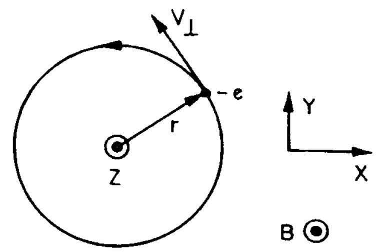


Fig. 3

with $v_\perp = \omega r$ (ω is the angular velocity of circular motion =cyclotron frequency)

gives $\omega = \dfrac{eB}{m}$

The time period of evolution is $T = \dfrac{2\pi m}{eB}$ **----------------------------------- (2)**

Note that **T** is independent of $v_\perp$

Along with the circular motion the electron has a longitudinal velocity $v_{||} \approx v$ which transforms the purely rotational motion to helical path (fig 4)

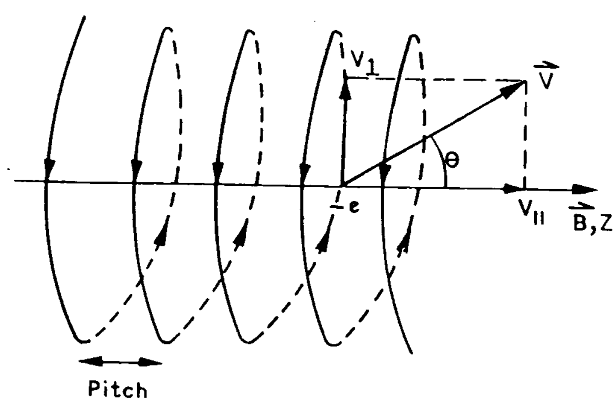


fig 4

I.4. The pitch of the helical motion is defined as longitudinal distance moved in one full rotational period i.e.

I.4. The pitch of the helical motion is defined as longitudinal distance moved in one full rotational period i.e.

$$\text{pitch} = v_{\parallel}\mathbf{T} \approx \frac{2\pi m v}{e B} \qquad \textbf{-----------------(3)}$$

I.5. When the magnetic field is switched on the line on the CRT rotates and shrinks. The AC deflecting voltage produces a range of "$v_{\perp}$" values (both +ve and –ve) for the transverse velocities of the electrons. The radii of different electrons will be different but all the electrons rotate through the same angle in the same time causing the line on the screen to rotate. (fig 5).

From fig.5 , it is clear that if each electron rotates through a full circle then the line on the CRT screen will shrink to a point .For this purpose to happen the distance **L** (from plate to screen of the CRT)should at least equal to one pitch of the helix . By adjusting **B** the pitch of the helix can be made equal to **L** and the lines becomes a point .This is called focusing action of the magnetic field.

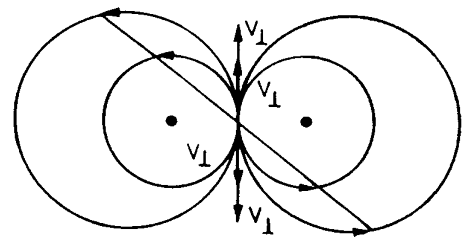


fig.5

I.6 At this value of magnetic, we have

$$\mathbf{L} = \text{pitch} = \frac{2\pi m v}{eB} \qquad \textbf{---------------------- (4)}$$

The velocity 'v' of the electron can be estimated using the accelerating V_a , by

$$(½)\, m v^2 = e\, V_a \Rightarrow \sqrt{\frac{2 e V_a}{m}} \qquad \textbf{---------------------------- (5)}$$

Thus,

$$L = \left(\frac{2\pi\sqrt{2V_a}}{B}\right)\sqrt{\frac{m}{e}}$$

giving,

$$\frac{e}{m} = \frac{8\pi V_a}{L^2 B^2} \qquad \textbf{--------------------------- (6)}$$

The value of the ratio (e/m) can be calculated knowing the accelerating voltage V_a the distance **L** and the magnetic field of the solenoid **B** .

II. Setup and procedure:

1. Insert the CRT in the solenoid approximately at the middle position. Place the axis of the solenoid parallel to the magnetic meridian. (This is to counter balance the effect of the Earth's magnetic field).

2. Insert the plug of the CRT to the base of the power supply.

3. Connect the DC power supply, rheostat & solenoid in series as shown in fig.6

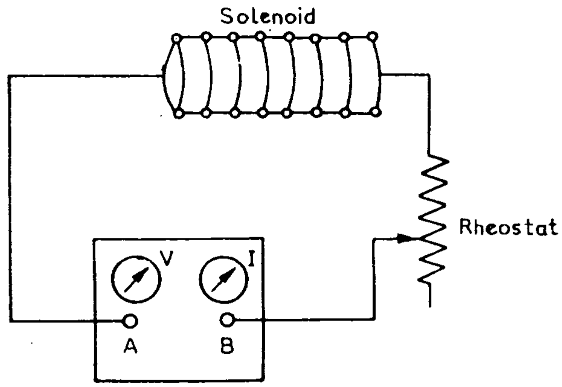


Fig 6

4. Let the DC power supply to solenoid be switched off to begin with. Switch on the power supply to the CRT. Select the AC supply in the 'Off' position .Use the intensity & the focus controls to obtain a point –like spot at the center of the screen. Next select the AC supply in the 'X' position and adjust the voltage using the control to get a line on the screen about 1.5 cm long .Using a voltmeter across the terminals of the accelerating voltage supply adjust the control to set the voltage V_a=250 V.

5. Switch on the DC power supply to the solenoid .As you increase the voltage the line on the screen shrinks and also rotates. Increase the voltage so that the line shrinks to a point on the screen. This is the focusing effect. If the does not completely shrink to a point in the voltage range available adjust the rheostat position till this is possible. Note down the current I_1 through the solenoid at this point.

6. Keeping all settings same, interchange the contact at A&B (fig 6). This reverses the direction of the current in the solenoid. Adjust the DC supply till a point like image is again obtained on the screen and record the current I_2.

7. Repeat step 4 & 6 for accelerating voltages V_a=275V & 300V.

III. Error analysis:

1. One of the major sources of error in the experiment is the horizontal component of earth's magnetic field $B_E=3.53 \times 10^{-5}$ T. This has partly been taken care of by our averaging procedure. Assuming that in the forward position the B_o adds to the solenoid field and that in the reverse position B_E reduces the solenoid field

   Then $$(e/m)_1 + (e/m)_2 = \frac{8\pi^2 V_a}{L^2 (B_1 + B_E)^2} + \frac{8\pi^2 V_a}{L^2 (B_1 - B_E)^2}$$

   Assuming B_E << B_1 & B_2 , one can Taylor expand the RHS to get the following

   $$\text{RHS} \cong \frac{8\pi^2 V_a}{L^2 B_1^2} + \frac{8\pi^2 V_a}{L^2 B_2^2} + \frac{16\pi^2 V_a}{L^2}\left(\frac{-B_E}{B_1^3} + \frac{B_E}{B_2^3}\right)$$

   The third term is negligible if $B_1=B_2$. Thus the average of $(e/m)_1$ & $(e/m)_2$ gives a value for e/m corrected for the earths magnetic field(B_E).

2. Another source of error in our expression (eq 6) for e/m is that we have used a constant value $v=\sqrt{\frac{2eV_a}{m}}$ for the velocity of the electron. This may be all right if the acceleration is completed before the electron starts traveling the distance L. However if the acceleration extends beyond the edge of the X plates, then our use of constant 'v' will lead to an over estimate of e/m.

3. A further source of error is due to fact that the solenoid is of a finite length. The magnetic field along the axis of the solenoid varies with position. The value $B=\mu_o n I$ is strictly valid only for an infinite solenoid (see exercise 5)

4. General error analysis:
Take a variation of eq (6) for e/m as a function of V_a , L & B . Add the magnitude of all the terms in the variation and divide the expression by e/m .this leads to the estimation of the fractional error as

$$\frac{\Delta(e/m)}{(e/m)} = \left|\frac{\Delta V_a}{V_a}\right| + 2\left|\frac{\Delta L}{L}\right| + 2\left|\frac{\Delta B}{B}\right| \text{ ---------------------------- } \mathbf{(7)}$$

ΔV_a & ΔL can be taken to be the least counts of the respective measuring instruments .The error in B i.e. $\Delta B = \Delta(\mu_o n I)$ can arise due to error in the current
measurement and error in counting the number of turns.

IV. Exercises and Viva Questions:

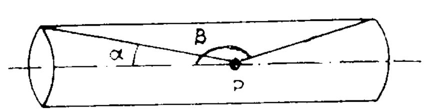
1. What will be the effect of the earth's magnetic field on the experiment? How is the effect accounted for in the experiment?

2. What will be the effect of keeping the solenoid axis perpendicular to the magnetic meridian?

3. Why does the line on the CRT screen rotate and shrink as the magnetic field is turned on?

4. What will be the difference in the experiment if the transverse deflecting voltage is DC instead of AC?

5. Evaluate the magnetic field on the axis of a solenoid of finite length (at point 'p' as shown in figure)



and show that it is given by

$$\mathbf{B} = (\mu_o n I / 2)(\cos\alpha + \cos\beta)$$

6. Derive equation (7).

7. Estimate the error $\frac{\Delta(e/m)}{(e/m)}$ in your experiment.

8. Refine the error estimate for the magnetic field by using exercise 5 and recalculate $\frac{\Delta(e/m)}{(e/m)}$.
9. What happens to the pattern on the screen if the solenoid current is continuously increased?

10. Compare this experiment with the Thomson's bar magnet method for measuring e/m.

References:

1. "Fundamentals of Physics", D.Halliday, R.Resnick and J.Walker, 6th edition, John-Wiley & sons, New York.
2. "Electricity & Magnetism" , A.S .Mahajan and A.A.Rangwalla ,Tata –McGraw Hill, New Delhi.

Experiment 9

Measurement of (e/m) by helical coil method.

Observations and Results

Constant values:

1. Distance between the edge of X deflecting plates and fluorescent screen, L = 9cm.

2. Total number of turns in the solenoid, N = 3350.

3. Length of the solenoid, l = ____________ cm.

4. Magnetic permeability of free space, $\mu_o = 4\,\pi \times 10^{-7}\ Nm^2 / Amp^2$.

Observation table :

	I_1= Solenoid current (forward direction)	**I_2** = Solenoid current (reverse direction)
1. $V_a = 250V$		
2. $V_a = 275V$		
3. $V_a = 300V$		

Solenoid current and accelerating voltage at focusing

Calculations and results:

1. $V_a = 250V$	$B_1 = (\mu_o N I_1) /(l)$	$(e/m)_1 = \dfrac{8\,\pi^2 V_a}{L^2 B_1^2}$ =	$(e/m)_{avg}$ =
	$B_2 = (\mu_o N I_1) /(l)$	$(e/m)_2 = \dfrac{8\,\pi^2 V_a}{L^2 B_2^2}$ =	
2. $V_a = 275\ V$	B_1 =	$(e/m)_1$ =	$(e/m)_{avg}$ =
	B_2 =	$(e/m)_2$ =	
3. $V_a = 300\ V$	B_1 =	$(e/m)_1$ =	$(e/m)_{avg}$ =
	B_2 =	$(e/m)_2$ =	

Results:

The calculated value of e/m =____________________C/kg.

The standard value of e/m =_____________________C/kg.

% Error in e/m =_____________________

Experiment 10

Charging and Discharging of a Capacitor

Apparatus:

Ballistic galvanometer, lamp, and scale, capacitor, resistor, solar cell, light filters, stop watch, two way switches, damping key , connecting wires .

Purpose of experiment:

i) To study the charging and discharging of a capacitor
ii) To measure the time constant characterizing charging / discharging process
iii) To understand the working of a ballistic galvanometer.

Basic Methodology:

A capacitor is charged by a solar cell and discharged (for different times) through a resistor and ballistic galvanometer .The deflection of the galvanometer is in proportion to the amount of charge that passes through it .A lamp and scale arrangement is used to measure the deflection.

I. Introduction:

I.1 The basic circuit for charging and discharging a capacitor is shown in fig 1. If switch S_1 is closed keeping S_2 open, then the battery charges the capacitor and current flows through the resistor R_1 until the capacitor is fully charged. If the charge on the capacitor at time **t** is **q(t)** , then the voltage across the capacitor **C** is **q/C** .and the current through R_1 is **i** = d**q**/dt .
By applying Kirchoff's second law,

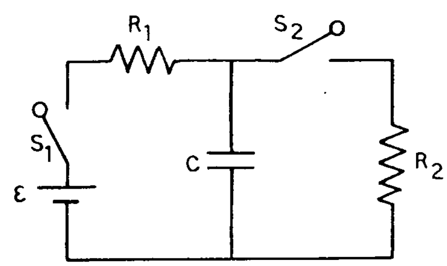


fig.1→

$$iR_1 + (q/C) = \varepsilon \quad \Rightarrow \quad R_1\ (dq/dt)+(q/C) = \varepsilon \text{ . -------------------- (1)}$$

which has the solution

$$q(t) = C\ \varepsilon(1 - \exp(-t / R_1 C)) = q_o(1 - \exp(-t / R_1 C)) \text{ -----------------(2)}$$

where $q_o = C\ \varepsilon$

The quantity $\tau = R_1C$ is the charging time constant which characterizes the rate at which charge is deposited on the capacitor .As $t \to \infty$, eq (2) shows that $q \to C\ \varepsilon = q_o$. In practice the capacitor charges to its maximum value q_o after a time interval equal to a few time constants. Once the capacitor is fully charged then the current **i** through the resistor become zero.

I.2 At this point if the switch S_1 is opened and S_2 is closed the charge in the capacitor discharges through the resistor R_2

By Kirchoff's second law

$$R_2\left(\frac{dq}{dt}\right)+\left(\frac{q}{C}\right)=0 \quad \text{-------------------------------------} \textbf{ (3)}$$

with the solution (taking $q=q_o$ at $t=0$)

$$q(t)=q_0 \exp\left(\frac{-t}{R_2 C}\right) \quad \text{--------------------------------------}\textbf{(4)}$$

Thus the charge on the capacitor decays exponentially with time. In fact after a time $t=R_2 C$ (equal to the discharging time constant) the charge drops from it's initial value q_o by a factor of e^{-1} .

II.2 In this experiment we will measure the quantity of charge present in the capacitor by discharging it through a ballistic galvanometer . The circuit for the experiment is shown in fig.2.

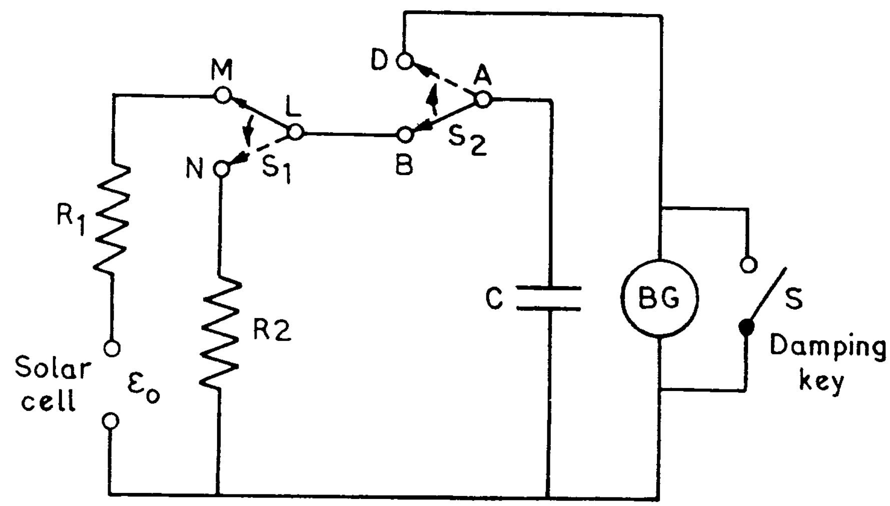


fig 2.

A solar cell generates emf upon being illuminated by a light source. The ballistic galvanometer is a sensitive detector of small quantities of charge. Thus, it is sufficient to charge the capacitor with solar cell, which typically produces an output of about 0.1 – 0.3 V. When the switch S_1 is in the position L → M and the switch S_2 is in the position A → B, then the capacitor gets charged. The time constant for charging is$\tau_1=R_1C$.If the switch $S_1$is in the position L → N, then the capacitor discharges through the resistor R_2. The time constant is $\tau_2=R_2C$**.** At any point of time the charge residing on the capacitor, can be measured by changing S_2 to the position A → D, discharging the capacitor through the ballistic galvanometer (BG).

II.3. Ballistic galvanometer:

A galvanometer is an instrument, which uses magnetic effects for detecting and measuring currents or electric charge. In a moving coil galvanometer, a flat conducting coil is suspended between the poles of a permanent magnet (fig 3). The coil consists of an insulated wire wound on light brass or aluminum frame.

The coil is usually suspended by a phosphor bronze strip, which also serves as the current lead for the current to the coil and is finally connected to a terminal at the base of the instrument. The other end of the coil is connected to a light spring, which provides the restoring couple. The other end of the spring is attached to the other terminal.

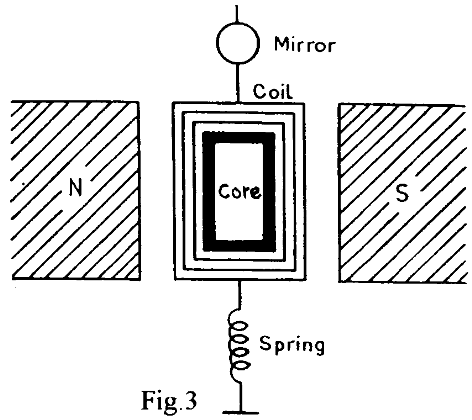


Fig.3

A ballistic galvanometer is used for the purpose of measuring the total charge in an impulse current as against measurement of a steady current. For this we require that the period of oscillation of the moving coil be large compared to the time for the current pulse passing through it. This is achieved by loading the coil so as to increase its moment of inertia. Thus when the current pulse passes through it , the coil receives a kick due to an impulse torque. Subsequently the coil oscillates freely due to the restoring torque provided by the suspension. The maximum deflection amplitude θ_o (called first throw position) is reached long after the current is passed. A necessary requirement is also that damping is small. The fact that the coil is kicked from rest (much like a bullet is shot of a gun) leads to the nomenclature ballistic galvanometer for the instrument.

The first throw position θ_o (maximum amplitude of deflection) is proportional to the total charge $\mathbf{q = \int i\, dt}$ in the current **i** passing through the coil. If **A** is the area of the coil , **n** is the number of turns of the coil and **B** is the magnetic field of the permanent magnet .Then the impulse on the coil is

$$\tau_G = \mathbf{n\,(i\,A)\,B}$$

leading to an initial angular momentum (**I** is the moment of inertia of the coil) ,

$$\mathbf{I\,\omega = \int \tau_G\, dt = n\,A\,B\,q} \qquad \text{---------------------------(5)}$$

If the restoring torque provided by suspension is $k\theta$, then equating the initial kinetic energy To the work done by the restoring torque , we get

$$\frac{1}{2}\mathrm{I}\,\omega^2 = \frac{1}{2}\mathrm{k}\,\theta_0^2 \qquad \text{-------------------------------- (6)}$$

which leads to (using eq 5),

$$q = \sqrt{\mathrm{Ik}}\;\frac{1}{\mathrm{n\,AB}}\,\theta_0$$

I

Substituting $\mathrm{T} = 2\pi\sqrt{\frac{\mathrm{I}}{\mathrm{k}}}$, the period of free oscillations, we get

$$q = \frac{\mathrm{T}}{\pi}\;\frac{\mathrm{k}}{\mathrm{n\,A\,B}}\;\frac{\theta_0}{2} \qquad \text{---------------------------------- (7)}$$

showing the proportionality relationship between q and θ_o.

The deflection of the coil is measured by the deflection of a light beam by the mirror attached to the coil (fig 4). This deflection is recorded as the linear deflection of the spot, X, that the reflected beam makes on the scale. Clearly X will also be directly proportional to the charge q discharged through the ballistic galvanometer. Thus, if the capacitor is discharged through the galvanometer after different charging / discharging times, the relation of X with time will be given by equations analogous to eqs (2) & (4).

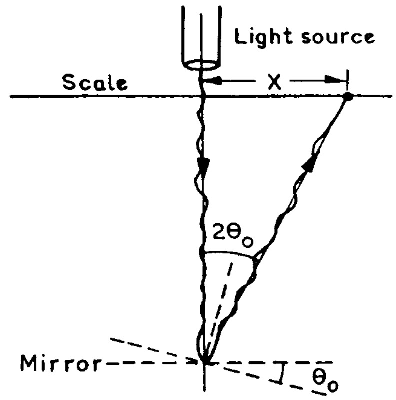


fig 4

Note the damping key S in fig (2). When passed, this simply shorts the two ends of the galvanometer coil. The oscillations of the coil get severely damped (why?). The damping key thus can used to stop the motion of the coil. .

II. Set - up and Procedure:

Part A: Measurement of time constant for charging of capacitor.

1. Connect the circuit as given in fig.2 with $R_1 = 0$ (i.e. without the resistance R_1). (This is to ensure that the charging of the capacitor by the solar cell is almost instantaneous)

2. Choose a filter for the light illuminating the solar cell. (The voltage output of the solar cell will depend on the intensity of the light illuminated it).

3. Switch on the lamp of the lamp and scale arrangement and adjust the arrangement so that a bright spot is obtained on the scale. Use the damping key S to bring the bright spot to rest. Note down the initial rest position of the spot.

4. Switch on the illumination to the solar cell with the key S_1 in the L → M position. The solar cell will then charge the capacitor.

5. After fully charging the capacitor (this should happen in the less than a minute), press the key S_2 to the A → D position. This will cause the capacitor to the discharge through the ballistic galvanometer. Note the deflection X_o of the first throw position of the spot.

   (Caution: The deflection should not be larger than about 20 cm. Causing too large to discharge through the galvanometer will cause a large and uncontrolled deflection of the coil which can damage the instrument. Choosing darker filter colours for the solar cell illumination can moderate the charge on the capacitor)

6. Depress the key S_2 so that it is in the A → B position and also set the key S_1 so that it is in the L → M (charging) position .Again fully charge the capacitor .

7. Set the key S_1 to the L → N position so that the capacitor discharges through the resistor R_2. Discharge the capacitor for a time t (t can be measured with the help

of a stop watch). At the end of the time t press S_2 to the A → D position and note the

first throw position X . Repeat for t = 10, 20, 30, 40, 50, 60 seconds.

8. Repeat the measurement for two different filters.

Part B: Measurement of time constant for charging of capacitor.

1. Add the resistance R_1 ($R_1 \sim 2$ M Ω) to the circuit as in fig 2 .Also remove the resistance R_2 from the circuit leaving the node N unconnected.

2. Choose a filter and switch on the solar cell and set the key S_1 in L → M position to charge the capacitor.

3. At the end of a time interval t (measured by stop watch) turn the switch S_1 to the L→N position. This halts the charging of the capacitor. Now depress S_2 to connect A → D discharging the capacitor through the galvanometer and note the first throw deflection X.

   (Note: You will need to take a large number of measurements (about 10 – 15) to get
   proper results .Also make sure there are sufficient measurements for times smaller than and for times greater than the time constant .You could choose the following measurements : t = 5 , 10 , 15 , 20 , …….60 seconds)

III. Exercises and Viva Questions:

1. Plot qualitatively the curves q(t) describing charging and discharging of a capacitor
   and explain these curves physically .

2. What is the physical meaning of the time constant τ= RC? Explain for both the cases of charging and discharging.

3. Estimate total charge deposited by the solar cell on the capacitor. Why do we need to use solar cell in the experiment?

4. What is the effect of changing the filter? Look at your observations and verify your
   expectations.

5. How does a ballistic galvanometer work? Why it is called so? Why do we need to use a ballistic galvanometer in this experiment?

6. Why is it necessary in a ballistic galvanometer, to have a relatively large moment of inertia for the moving coil and small damping ?

7. What is the effect on the galvanometer deflection on pressing the damping key? Explain why the damping is produced?

8. What would be the effect on the experiment if resistances of the order of 100Ω or 1 kΩ were used?

9. By what percentage (with respect to the maximum charge on the capacitor $C\varepsilon$), does the capacitor charge / discharge in a time interval $t = \tau$, $t = 2\tau$ (τ = time constant)?
10. Estimate the width of the current pulse that passes through the ballistic galvanometer when the capacitor is discharged through it .You may need to have an idea of the intrinsic resistance of the galvanometer.

References:

1. "Physics", M.Alonso and E.J.Finn, Addison-Wiley, 1992

2. "Fundamentals of Physics", D.Halliday, R.Resnick and J.Walker,6th edition, John-Wiley & sons, New York 2001.

Experiment 10

Charging and Discharging of a Capacitor

Observations and results

Part A: Measurement of time constant for discharging of a capacitor

R_2 = ________________________

C = ________________________

PART A : Measurement of time constant for discharging of capacitor

Table 1

Rest position of spot on the scale = ______________________

S.No	Discharging time t (sec)	First throw position X (cm)		ln X	
		Red	Green		
1	0				
2	10				
3	20				
4	30				
5	40				
6	50				
7	60				

Calculations:

Plot the graph of **ln X** vs. **t** and draw a best fit straight line .Obtain the time constant from slope (= $-1 / R_2 C$) of the line .

Slope =

$\tau = -(1/\text{slope}) =$

Results:

The value of time constant measured **τ =** ___________________ sec

The value of time constant calculated **τ =**___________________ sec

Part B: Measurement of time constant for charging of capacitor

Table 2

Rest position of spot on scale =___________________

S No	Charging time t (sec)	First throw position X (cm)
1	0	
2	5	
3	10	
4	15	
5	20	
6	25	
7	30	
8	35	
9	40	
10	45	
11	50	
12	55	
13	60	
14	65	
15	70	

Calculations:

Plot the graph X vs. t and fit a smooth curve. Draw an asymptote to the graph for large values of t. Estimate the asymptotic value X_o for X for large values of t. From the graph estimate the time at which $X = X_o\,(1- e^{-1}) = 0.63\,X_o$. This time is an estimate of the charging time constant $\tau = R_1 C$. Explicitly
Show the procedure on the graph.

Results:

1. Estimated value of time constant τ = ___________________

2. Calculated value of time constant **τ =** R_1C **=** _________________

(*Two graph papers required).*

Experiment 11

Self Inductance and resistance of a coil

Objective :

To determine the self inductance and resistance of a coil with air core and iron core.

Theory:

Let us consider an R-L circuit connected to an ac supply as shown in *Fig 1*. Practically it is not possible to have an ideal inductor at room temperature. The present inductor coil has a self inductance of 'L' and resistance 'r'. Let V_1 be the voltage drop across the coil which is the combination of voltage drop due to inductance 'L' and resistance 'r'. Let V_L and V_r be the voltage drop due to the inductive and resistive parts of the coil. From *Fig.2*

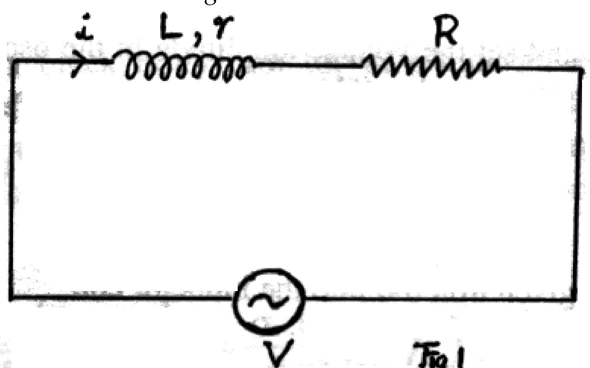


Fig 1

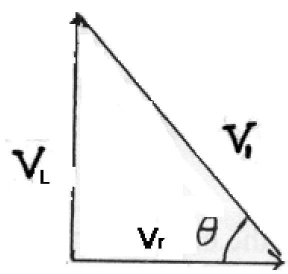


Fig 2

$V_1 = \sqrt{(V_L^2 + V_r^2)}$ --------------------------------(1)

Let V_2 be the voltage drop across the resistor 'R' and 'V' be the total voltage drop across the R-L Circuit. The complete phase diagram is shown in *Fig 3*.

From Fig.3,

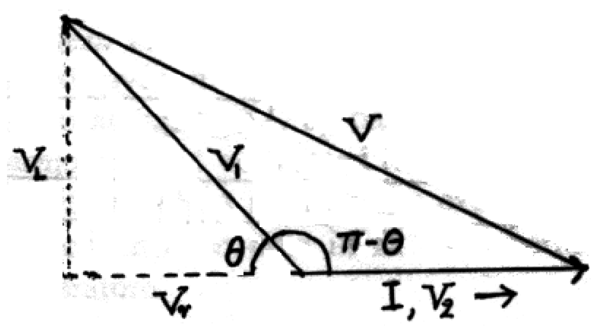


Fig 3

$V^2 = V_1^2 + V_2^2 - 2V_1V_2Cos(\pi - \theta)$

Or

$V^2 = V_1^2 + V_2^2 + 2V_1V_2Cos(\theta)$ …(2)

$V_r = V_1 \cos\theta$ --------------------(3)

$V_L = V_1 \sin\theta$-------------------- (4)

Also $V_L = I.L.\omega$ ------------------(5)

and $V_r = I r$--------------------- (6)

By measuring the voltage V across resistor R, current I in the circuit can be determined. Measure V_1, V_2, and V to determine L and r using equations (2) to (6).

Procedure:

1. Connect the R-L circuit to the oscillator using the given resistor and inductor coil (Fig. 1).

2. Set the oscillator frequency to 2 KHz and set the voltage amplitude in the oscillator such that the voltage drop across the inductor does not exceed certain Volts (….).

3. Measure the voltage drops V_1, V_2 and V for different values of R (Table 1).

4. Repeat the experiment by inserting an iron rod into the inductor coil.

From eq (2) to eq (6) calculate the inductance L and resistance r of the coil for air core and iron core and plot them as a function of current in the circuit.

Table1

Sl No.	R(ohms)	V(volts)	V_1(volts)	V_2(volts)

Table2

Sl No	R(ohms)	I(amps)	L(mH)	R(ohm)

Experiment 12

Resonance in LCR circuits

Apparatus:

Oscillator (1 to 150 kHz), variable capacitor, resistance, resistance box, AC mill voltmeter.

Purpose of the experiment:

To study resonance effect in series and parallel LCR circuit. *This experiments also enables study of forced damped oscillation.*

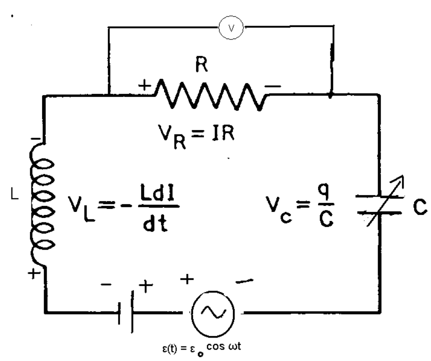
Basic methodology:

In the series LCR circuit, an inductor (L), capacitor (C) and resistance(R) are connected in series with a variable frequency sinusoidal emf source and the voltage across the resistance is measured. As the frequency is varied, the current in the circuit (and hence the voltage across R) becomes maximum at the resonance frequency $\nu_0 = \dfrac{1}{2\pi\sqrt{LC}}$. In the parallel LCR circuit there is a minimum of the current at the resonance frequency.

I. Introduction:

I.1 There is in general an analogy between resonating mechanical systems (like a driven spring mass system) and electrical systems involving inductors, resistor and capacitors. In the electrical case it is the charge q(t) on the capacitor (or the current I= dq/dt) that satisfies a differential equation analogous to the displacement of the mass in the familiar spring mass system.

Consider the circuit fig 1 consisting of an inductor (L) , capacitor (C) and a resistance(R) connected in series with a source of sinusoidally varying emf $\varepsilon(t) = \varepsilon_0 \cos \omega t$. Equating the voltage drops across the resistor and capacitor to the total emf, we get,



$RI + (q / C) = V_L + \varepsilon_0 \cos \omega t$ **Fig.1→**

$= - L (dI / dt) + \varepsilon_0 \cos \omega t$ **--------------(1)**

Differentiating the equation with respect to time and rearranging, we get

$L (d^2 I / dt) + R (dI / dt) + (I / C) = - \omega\varepsilon_0 \sin \omega t$ **----------------------(2)**

which is analogous to the equation of motion for a damped oscillator .

The current I(t) has the solution

$I(t)= I_0 \cos (\omega t - \alpha)$ **-------------------------------------(3)**

where I_o exhibits resonance behaviour . The amplitude I_o is given by

$$I_0 = \frac{\varepsilon_0}{\left[R^2 + \left(\omega L - \frac{1}{LC}\right)^2\right]^{1/2}} \qquad \text{----------------------(4)}$$

$$\operatorname{Tan}\alpha = \frac{\omega L - \frac{1}{\omega C}}{R} \qquad \text{-------------------------------(5)}$$

Gives the phase of the current relative to the applied emf. We can write $I_o = \varepsilon_0 / Z$ where ,

$$Z = \left[R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right]^{1/2} \qquad \text{-------------------------(6)}$$

is the impedance of the circuit .The reactance X of the circuit is

$$X = \omega L - \frac{1}{\omega L}, \qquad \text{---------------------------(7)}$$

so that the impedance Z is given by

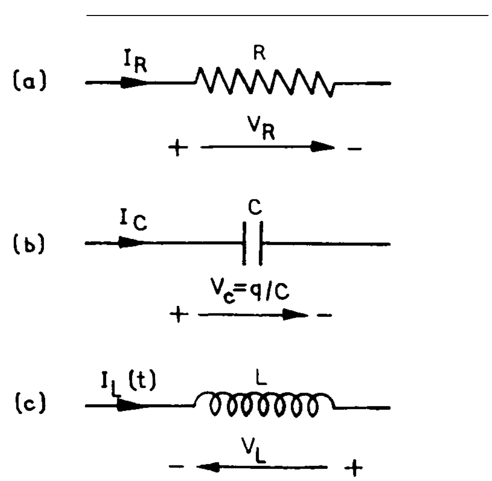
$$Z = (R^2 + X^2)^{1/2}$$

Clearly the impedance will be minimum (and I_o will be maximum) at resonance condition when the reactance vanishes, i.e.. at the angular frequency (known as resonance frequency)

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \text{-------------------------------(8)}$$

which is the natural frequency of electromagnetic oscillations in LCR circuit without an external source of emf .

I.2 Resistance, Capacitance and Inductance in AC circuits:



Consider a resistor with a voltage drop $V_R = V_{RO} \cos(\omega t)$ across it (fig 2a). By Ohm's law the current through resistor is

$$I_R = \frac{V_R}{R} = \frac{V_{R0}}{R} \cos \omega t \qquad \text{--------------(9)}$$

The current and the voltage across a resistor are in phase.

In the case of a capacitor (fig 2b) the current $I_C = dQ/dt$ where q is the charge on the capacitor .If the potential drop across the capacitor is $V_C = V_{CO} \cos \omega t$, the charge q

$= CV_C = CV_{CO} \cos\omega t$ **fig2**

$$I_C = -\,\omega C V_{CO} \sin \omega t = \omega C V_{CO} \cos\left(\omega t + \frac{\pi}{2}\right) \qquad \textbf{------------10)}$$

Thus the current through the capacitor is ahead of voltage by phase angle **π/2.** Consider now an inductor (fig 2c) with current $I_L(t) = I_{LO} \cos \omega t$. Assume that the current flows and increases in the direction shown. The back emf induced in the inductor opposes the
current and the potential drop across the inductor is

$$V_L = L\,(dI / dt) = -\,\omega L I_{LO} \sin \omega t = \omega L I_{LO} \cos(\omega t + \pi/2) \textbf{----------(11)}$$

The voltage across the inductor is ahead of the current in phase by an angle $\pi/2$

I.3 Complex Impedance:

It is convenient to use complex phasors to represent the current and voltage in an AC circuit. For example, the phasor $\overline{V} = V_o e^{i\omega t} = V_o(\cos\omega t + j\sin\omega t)$ represents a sinusoidal varying voltage $V_o \cos \omega t$ which is its real part .For any component A we define its complex impedance by $\overline{V}_A = \overline{Z}_A\ \overline{I}_A$. We write

$$\overline{Z} = R + jX \quad ,$$

Where the real part of $\overline{Z}$ is the resistive impedance (R) , while the imaginary part of $\overline{Z}$ is the reactive impedance (X).

The complex impedances of the resistor, capacitor and the inductor can be obtained by generalizing eqs (9) ,(10) & (11) to phasor equations :

$$\overline{I}_R = \frac{1}{R}\overline{V}_R \Rightarrow Z_R = R \qquad \textbf{---------------------------------------(12)}$$

$$\overline{I}_C = \omega C V_{CO}\, e^{j\left(\omega t + \frac{\pi}{2}\right)} = j\omega C\overline{V}_C \Rightarrow \overline{Z}_C \Rightarrow \overline{Z}_C = \frac{1}{j\omega C} \qquad \textbf{--------------------(13)}$$

$$\overline{V}_L = \omega L I_L\, e^{j\left(\omega t + \frac{\pi}{2}\right)} = +j\omega L I_L \Rightarrow \overline{Z}_L = j\omega L \qquad \textbf{--------------------------------(14)}$$

Thus the impedance of a resistor is its resistance itself, while the impedance of a capacitor and inductance are reactive with $X_C = -\,1/(\omega C)$ and $X_L = \omega L$.

It can be shown from Kirchoff's rules that complex impedances in series or parallel combine just like resistors in series or parallel. Thus, for the series LCR circuit fig 1, the net impedance of the circuit is

$$\overline{Z} = \overline{Z}_R + \overline{Z}_C + \overline{Z}_L = R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad \textbf{-------------------------------------(15)}$$

The current flowing in the circuit is then

$$\overline{I} = \frac{\overline{\varepsilon}}{\overline{Z}} = \frac{\varepsilon_o\, e^{j\omega t}}{R + j\left(\omega L - \frac{1}{\omega C}\right)} = I_o\, e^{j(\omega t - \alpha)} \qquad \textbf{-------------------------------(16)}$$

From eq (16) it can be easily seen that

$$I_O = \frac{\varepsilon_O}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \quad (= \mathrm{Re}\,\bar{I})$$

and $$\alpha = \mathrm{Tan}^{-1}\left(\frac{\omega L - \frac{1}{\omega C}}{R}\right)$$

which clearly reproduces eqs (4) & (5) . The physical current in the circuit is, of course,
the real part of the phasor $\bar{I}$ in eq (16).

I.4. Parallel LCR circuit :

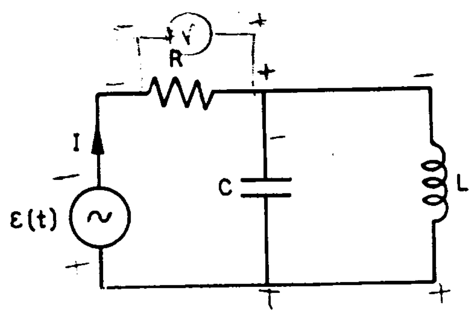


Fig 3

Consider now the parallel LCR circuit shown in fig 3. The current through the resistor can be found by calculating the equivalent impedance of the circuit.

$$\bar{Z} = \bar{Z}_R + \frac{1}{\left(\frac{1}{Z_C}\right) + \frac{1}{\bar{Z}_L}} = R + \frac{\bar{Z}_L\ \bar{Z}_C}{\bar{Z}_C + \bar{Z}_L} = R - j\frac{L/C}{\omega L - \frac{1}{\omega C}} \quad \textbf{--------------------(17)}$$

Thus

$$\bar{I} = \frac{\bar{\varepsilon}}{\bar{Z}} = \frac{\varepsilon_O\, e^{j\omega t}}{R - j\left(\frac{L/C}{\omega L - \frac{1}{\omega C}}\right)} = I_O\, e^{j(\omega t + \varphi)} \quad \textbf{---------------------------------(18)}$$

The magnitude of current I_O is given by

$$I_O = \frac{\varepsilon_O}{\sqrt{R^2 + \left(\frac{L/C}{\omega L - \frac{1}{\omega C}}\right)^2}} \quad \textbf{---------------------------------(19)}$$

Viewed as a function of ω, it is clear that I_O is now a minimum (the impedance in the denominator is maximum) when $\omega L = 1/(\omega L)$, or ,where

$$\omega = \frac{1}{\sqrt{LC}} = \omega_O \qquad \text{--}\mathbf{(20)}$$

and is known as "resonance frequency" even though it corresponds to an amplitude minimum .

(Note: The amplitude of current in eq (19) strictly falls at $\omega = \frac{1}{\sqrt{LC}}$ since the denominator tends to infinity. This is because we have considered idealized (i.e resistance less) capacitor and inductor. A finite value of current amplitude at resonance will be obtained if resistive impedance is included for these components)

I.5. Power Resonance:

The power dissipated at the resistor is P = I V = I^2 R = V^2 / R. From eq (3) for the series resonance circuit, the power dissipated at the resistor is

$$P = I_O^2 R \cos^2(\omega t - \alpha) \qquad \text{------------------------------------}\mathbf{(21)}$$

where I_O is given by eq (4) . The average power dissipated over one cycle is

$$\overline{P} = \frac{I_O^2 R}{2} = \frac{\varepsilon_O^2 \ R}{2\left[R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right]} \qquad \text{------------------------------}\mathbf{(22)}$$

Fig 4 shows graph of $\overline{P}$ as a function of the driving frequency ω. The maximum power value $\overline{P}_m$ occurs at the resonating frequency $\omega_O = \frac{1}{\sqrt{LC}}$. It can be shown that to a good approximation, which the power falls to half of the maximum value, $\overline{P}_m / 2$ at $\omega = \omega_O \pm \frac{\gamma}{2}$.

Here γ is related to damping in the electrical circuit and is given by $\gamma = R/L$.

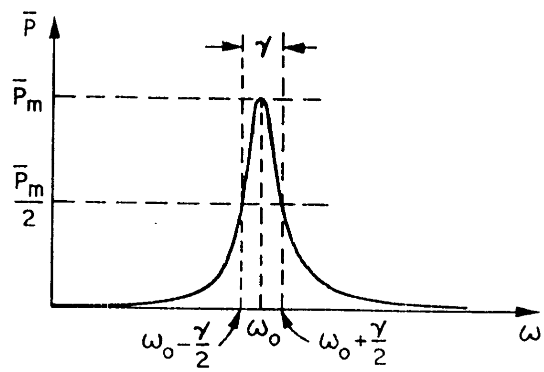


Fig .4

The width or range of ω over which the value of $\overline{P}$ falls to half the maximum at the resonance is called the Full Width Half Maximum (FWHM). The FHWM is a characteristic of the power resonance curve and is related to the amount of damping in the system. Clearly FWHM = $\gamma = \frac{R}{L}$. One also define the quality factor Q as $Q = \frac{\omega_O}{\gamma} = \frac{1}{R}\sqrt{\frac{L}{C}}$ which is also a measure damping. Large Q(small R) implies small damping while small Q(large R) implies large damping . Clearly we have

$$FWHM = \gamma = \frac{R}{L} \qquad \text{--------------------------------}\mathbf{(23)}$$

Thus, the quality factor Q can be determined from the FWHM of the power resonance graph.

II. Set-up and Procedure:

1. The series and parallel LCR circuits are to be connected as shown in fig 1 & fig 3.

2. Set the inductance of the variable inductance value and the capacitances the variable capacitor to low values (L ~ 0.01H , C ~ 0.1μ F) so that the resonant frequency

$$\nu_0 = \frac{1}{2\pi\sqrt{LC}} \text{ is of order of a few kHz .}$$

3. Choose the scale of the AC mill voltmeter so that the expected resonance occurs at approximately the middle of the scale.

4. Vary the frequency of the oscillator and record the voltage across the resistor.

5. Repeat (for both series and parallel LCR circuits) fir three values of the resistor (say R = 100 ,200 & 300 Ω).

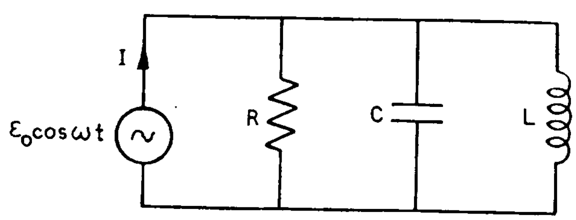
III. Exercises and Viva Questions:

1. Write down the Newton's law for a forced damped harmonic oscillator and map the electrical quantities appearing in eq (2) with corresponding mechanical quantities.

2. Verify that the solution, eq (3) satisfies the differential equation (2).

3. Distinguish between resistive impedance and reactive impedance. What is the effect of reactive impedance on the current and voltage in an AC circuit? In a DC circuit?

4. For the circuit shown with emf $\varepsilon(t) = \varepsilon_0 \cos \omega t$, determine the current $I(t) = I_0 \cos (\omega t - \alpha)$. (i.e. determine the amplitude I_0 and phase α).



5. Calculate the (resistive or reactive) impedance of the components L, C and R at resonance for series and parallel circuits , for your experiment .

6. Why does the series circuit give a power maximum at resonance while the parallel circuit lead to a power minimum ?

7. The AC mill voltmeter gives the 'rms' value of the voltage across the resistor, i.e. V_{rms} .

   If $V = V_0 \cos \omega t$, what is V_{rms} ? Show that the average power $\overline{P} = V_{rms}^2 / R$.

8. Show that eq (22) can be written as

$$\overline{P} = \frac{\varepsilon_0^2 R L}{2C} \frac{1}{\left[Q^2 + \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)^2 \right]}$$

9. Qualitatively plot the power resonance curve for increasing values of Q .Show that the

   FWHM of the power resonance curve is approximately given by $\gamma = \frac{\omega_0}{Q}$.

10 Argue why the power maximum(minimum) for the series (parallel)LCR circuit increases.

Reference:

1. “Physics”, M.Alonso and E.J.Finn, Addison-Wiley, 1992
2 “Linear Circuits”, M.E.Van Valkenburg and B.K Kinariwala , Printice Hall, Englewood Cliffs ,NJ ,1982.

Experiment 12

Resonance in LCR circuits

Observations and results

Part A: Series LCR Circuit.

L = ________________________ mH

C = ________________________ μF.

Table 1

S.No	Frequency ν (kHz)	R_1 = __________Ω		R_2 = __________ Ω		R_3 = __________ Ω	
		V	$\overline{P} = V^2/R$	V	$\overline{P} = V^2/R$	V	$\overline{P} = V^2/R$
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Part B: Parallel LCR Circuit

L = __________________ mH

C = __________________ μF.

Table 2

S.No	Frequency ν (kHz)	R_1 = __________Ω	R_2 = __________ Ω	R_3 = __________ Ω

		V	$\overline{P} = V^2/R$	V	$\overline{P} = V^2/R$	V	$\overline{P} = V^2/R$
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Calculations and Results:

1. Plot the graph of frequency (ν) vs $\overline{P}$ (average power) for series and parallel cases.

2. Read off the resonant frequency $\nu_o = \dfrac{1}{2\pi\sqrt{LC}}$ by locating the maxima / minima in the graphs
   i). Resonance frequency for series LCR circuit =________________kHz

   ii) Resonance frequency for parallel LCR circuit =________________kHz

   iii). Calculate the value of resonance frequency =________________kHz

Results :

Estimated value of Q for series resonance from graph : (1) (2) (3)

Calculated value of $Q = \dfrac{1}{R}\sqrt{\dfrac{L}{C}}$ = (1) (2) (3)

% errors in Q (1) (2) (3)

(One graph paper required).

Experiment 13

Hysterisis loop for a ferromagnetic material (M–B curve)

Apparatus:

Two solenoid coils, S and C, ferromagnetic specimen rod, reversible key (R), ammeter, magnetometer, battery, solenoid, rheostat and transformer for demagnetizing set up.

Purpose of experiment:

i) To study the magnetization (M) of a ferromagnetic material in the presence of a magnetic field B and to plot the hysterisis (M vs. B) curve .

ii) To calculate the retentivity and coercivity of the material.

Basic Methodology:

A ferromagnetic rod is magnetized by placing it in the magnetic field of a solenoid. The magnetized rod causes a deflection (θ) in a magnetometer .The deflection θ is recorded as the current in the solenoid (I) is varied over a range of positive and negative values .

I. Introduction:

I.1 The magnetic field of a solenoid at a point on its axis is

$$B = \mu_O \, n \, I \qquad \text{----------------------------(1)}$$

where $\mu_O = 4\pi \times 10^{-7}\ Nm^2 / A^2$ is the magnetic permeability of vacuum , n is the number of turns per unit length in the solenoid and I is the current in the solenoid .

I.2. The specimen rod is placed along the axis of the solenoid acquires a magnetization M along its axis. (Magnetization is defined as the magnetic dipole moment per unit volume). The magnetic dipole moment 'm' of the rod is

$$m = M\,(l\,\alpha) \qquad \text{-------------------------(2)}$$

where l = length of the rod and α = cross-sectional area of the rod .

I.3. The magnetic field produced by the rod at the position of the magnetometer (r) is

$$B_m = \frac{\mu_O}{4\pi}\frac{2mr}{\left(r^2 - \frac{l^2}{4}\right)} \qquad \text{------------(3)}$$

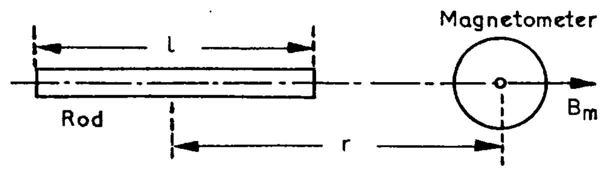


fig 1

I.4. The apparatus is aligned so that the horizontal component of the earth's magnetic field B_E , which is along South – North direction , is perpendicular to the axis of the rod (which is along the East –West direction). The magnetometer needle aligns along the resultant magnetic field making an angle θ with B_E as in fig 2.

Clearly,

$$\mathrm{Tan}\,\theta = \frac{B_M}{B_E} \;\Rightarrow B_M = B_E\,\mathrm{Tan}\,\theta \text{ -------}$$

(4)

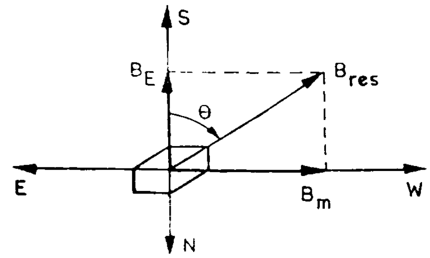


fig .2

I.5 Using eqs 2, 3 & 4 we can write

$$M = \frac{4\pi}{\mu_O\,\alpha(21)}\;\frac{\left(r^2 - 1^2/4\right)^2}{r}\,B_E\,\mathrm{Tan}\,\theta \text{ -------}$$

(5)

Hence $M \propto \mathrm{Tan}\,\theta$. Also from eq 1, $B \propto I$. Therefore a plot of Tan θ vs. I reproduces the features of M vs. B curve .

I.6 Hysterisis:

A ferromagnetic material whose atoms behave like magnetic dipoles produced by the spins of unpaired electrons. Domains form in the interior of the material with in which the dipoles align in a given direction but the domains themselves randomly oriented. (Fig 3)

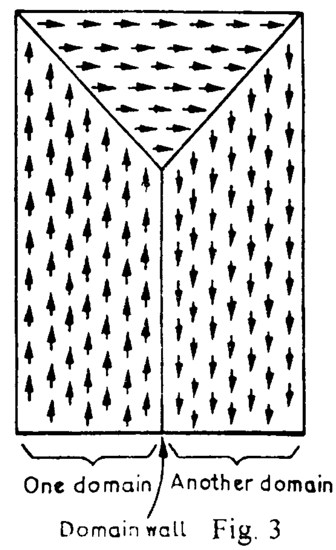


Fig. 3

In the presence of an external magnetic field the different domain moments tend to align producing a net magnetization in the direction of the magnetic field.

The variation of the magnetization M as the magnetic field B is varied gives rise to a characteristic curve called the hysterisis loop. Figure 4 shows a typical curve obtained. (The axes are taken to be Tan θ & I as is to be done in the experiment). As the magnetic field is increased the magnetization of the sample increases as more and more domains align along the direction of the magnetic field. With further increase in B, the magnetization M saturates to a maximum value (point b). If the current I (field B) is decreased the magnetization M decreases.

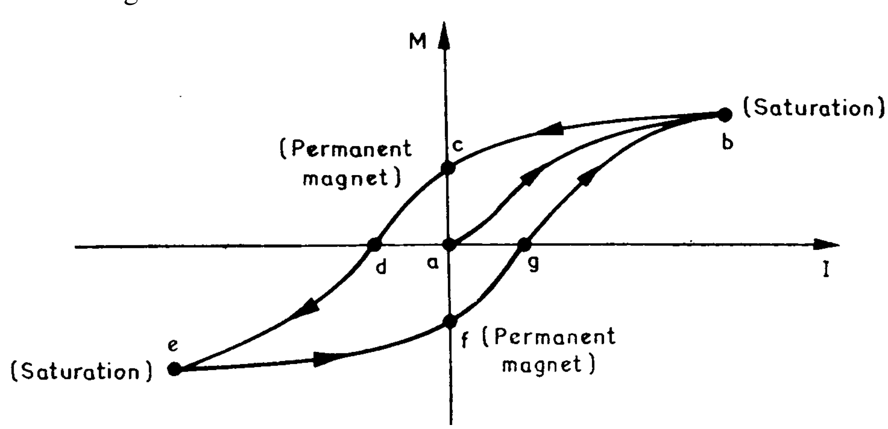


Fig 4

When the current is made zero (point c) the magnetization M however does not fall to zero. At this point the material has a residual magnetization and behaves like a permanent magnet. To make the magnetization zero (point d) requires a non-zero current in the reverse direction. As I is increased in the reverse direction, M saturates to a maximum negative value (point e). Further increase in the current brings the magnetization to zero (point g) and eventually to saturation (point b).

I.7 Retentivity & Coercivity:

Retentivity (M_O) is the residual magnetization in the sample when the external magnetic field is zero .
This is calculated as

$$M_O = \frac{4\pi}{\mu_O \alpha 2l} \frac{\left(r^2 - l^2/4\right)^2}{r} B_E \, Tan\,\theta_O \qquad \textbf{------------------------(6)}$$

Where, $Tan\,\theta_O = \frac{c\,f}{2}$ (c & f are the points in the graph, fig 4) **---------------(7)**

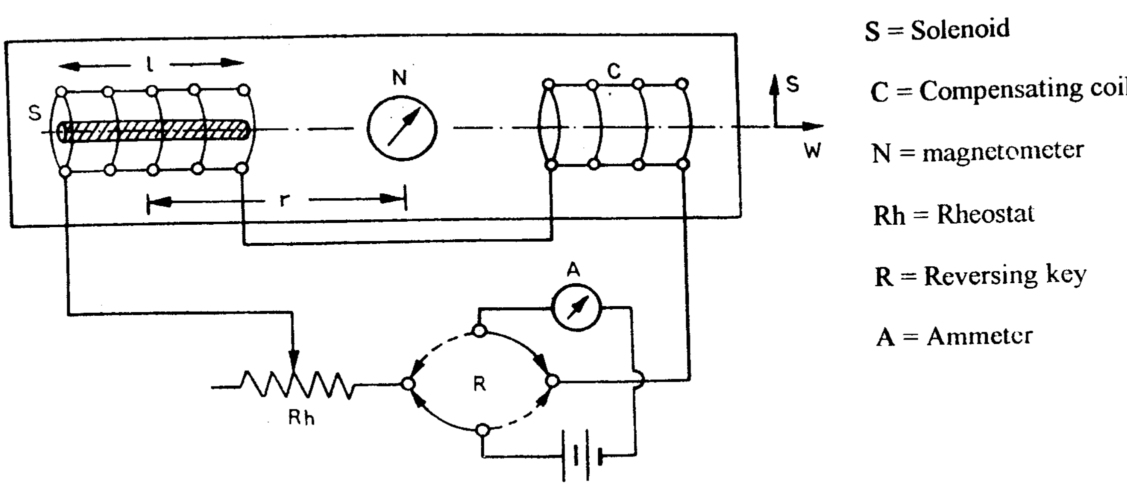
Coercivity B_O is the external magnetic field required to reduce the residual magnetization in the sample to zero.

$$I_O = \frac{d\,g}{2}\ ;\ B_O = \mu_O\, n\, I_O \qquad \textbf{------------------------------(8)}$$

(d & g are the points in the graph , fig 4)

II Set-up and procedure:

1. Complete the wiring of the apparatus according to the circuit diagram, fig 5



2. Alignment of apparatus:
   Rotate the dial of the magnetometer until $0^0 - 0^0$ position is aligned with the axis of the solenoid. Rotate the wooden arm, containing the solenoid, magnetometer and compensating coil, until the magnetic pointer coincides with the $0^0 - 0^0$ position. In this position the wooden arm is along the E – W position .The horizontal component of earth's magnetic field B_E (along S-N direction) is then perpendicular to the wooden arm.

3. Demagnetization of specimen:

Complete the wiring of the demagnetizing apparatus according to circuit Fig 6. Insert specimen rod in the solenoid and vary the AC current in the solenoid using rheostat. This procedure should take 2-5 minutes.

4 Positioning of the Compensating Coil:
Pass current (say 1A) through the coils S & C. Vary the position of C along the wooden arm until the deflection of the needle is zero.

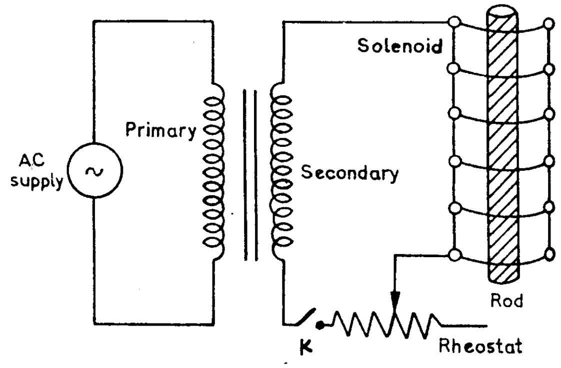


Fig 6

The magnetic field of solenoid S is then nullified (at the position of magnetometer)
by the magnetic field of C .

5. Begin Measurement:

i). To begin with, the current in the solenoid should be switched off.

ii). Insert specimen rod so that it's leading tip is at the edge of the solenoid.
(Note: There should be no deflection of the needle at this point .If deflection is observed, repeat step 3 for demagnetizing rod).

iii). Keep the reversing key R in a position so that current flows in a given direction.
The rheostat position should correspond to maximum resistance.

iv). Switch on the current.
(Caution: From now on the current variation sequence has to be followed strictly Any change or back tracking of measurement will lead to incorrect results).

v). Vary the current using the rheostat from 0A – 1.5A and back 1.5A – 0A insteps of 0.1A and note the deflections θ_1 & θ_2 for each setting of current.
(Caution: To get strictly zero current you will have to switch off the battery)

vi). Reverse the position of the reversible key R and vary the current in the reverse direction 0A – 1.5A ,and back 1.5A – 0A .Note the deflections θ_1 & θ_2

vii). Reverse the position of the key R and vary the current from 0 – 1.5A. Again note the deflections θ_1 & θ_2

III. Exercises and Via Questions:

1. Define paramagnetic, diamagnetic & ferromagnetic substances. Give one example of each.

2. Why the M vs. B curve called the hysterisis curve?

3. Derive eq (6).

4. What is the need to align the solenoid along the E – W direction?

5. Will the hysterisis curve be different if this alignment were not done? If yes why?
6. How does the demagnetization setup demagnetize the rod?

7. It is said that dropping the specimen rod on a hard surface also serves to remove any small residual magnetization . Is it true ? If so give reason.

8. Draw a small figure showing how the hysterisis curve would develop over many cycles of the current.

9. How would the retentivity & coercivity change with temperature? Do you think that they should depend on the geometry of the sample?

10. Identify the main sources of error in your experiment.

References:

1. "Fundamentals of Physics", D.Halliday, R.Resnick and J.Walker, 6th edition, John-Wiley & sons, New York 2001.

2. "Physics", M.Alonso and E.J.Finn, Addison-Wiley, 1992.

3. "Introduction to Electrodynamics", D.J.Griffiths ,PHI, 1998.

Observations and results

1. Distance, r = ____________________________ m

2. Length of specimen, l = ____________________ m

3. No. of turns per unit length of solenoid , n = 1600 turns/m .

4. Area of cross-section of rod , S = 1.84 x 10^{-5} m^2 .

5. Horizontal component of earth's magnetic field ,B_E = 3.53 x 10^{-5} T .

Table : Current through S & deflection θ

Current I (A)	Deflection (forward current) Degree.				Deflection (reverse current) Degree				Deflection (forward current)			
	θ_1	θ_2	θ_{avg}	Tan θ	θ_1	θ_2	θ_{avg}	Tan θ	θ_1	θ_2	θ_{avg}	Tan θ
0												
0.1												
0.2												
0.3												
0.4												
0.5												
0.6												
0.7												
0.8												
0.9												
1.0												
1.1												
1.2												
1.3												
1.4												
1.5												
1.4												
1.3.												
1.2												
1.1												
1.0												
0.9												
0.8												
0.7												
0.6												
0.5												
0.4												
0.3												
0.2												
0.1												
0												

Calculations:

1. Attach graph of Tanθ vs. I.

2. cf = ______________________

   dg = _____________________

3. Calculation of retentivity M_O :

   Calculation of coercivity B_O :

Results:

Retentivity M_O = ________________

Coercivity B_O = _________________

(One graph paper required).

Experiment 14

Electromagnetic Induction

Apparatus:

Metallic semi–circular arc (radius 40 cm), supporting frame, movable weights, bar magnets measurement board consisting of voltmeter, milli – ammeter, resistance condenser and diode.

Purpose of experiment:

To verify Faraday's laws of electromagnetic induction.

Basic Methodology:

A bar magnet is made to pass through a coil .The resulting emf produced by Faraday's effect charges a capacitor .The voltage of the capacitor is a measure of the induced emf .

I. Introduction

I.1 Faraday's law states that a charge in magnetic flux ($\mathbf{\Phi}$) through a closed conducting circuit induces an electro motive force (emf) ε in the circuit .

$$\varepsilon = -\frac{d\Phi}{dt} \qquad \text{-------------------------------(1)}$$

The emf ε is proportional to the rate of change of the flux through the coil. The minus sign is related to the fact that the induced emf opposes the change in the flux linking the circuit .In MKS system ε has units of Volts (V), while $\mathbf{\Phi}$ units of Weber (W) .In this experiment we will measure certain effects leading from Faraday's law and will hence indirectly verify the law.

The setup (fig1) basically consists of a bar magnet attached to a metallic arc. The frame the arc is suspended at the center so that the whole frame can freely oscillate in its plane. Movable weights are provided on the diagonal arm whose position is can be altered, leading to a variation of the period of oscillation from about 1.5 sec to 3 sec. As it oscillates the magnet passes through two copper coils. (Connected in series) of about 10,000 turns.

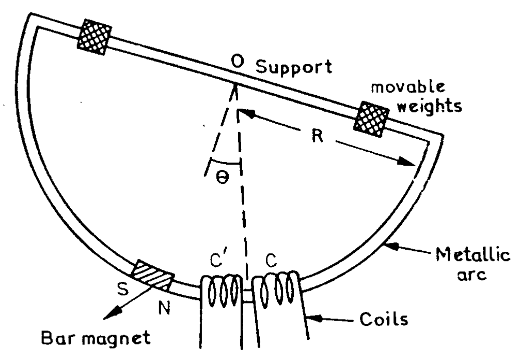


fig 1

As the magnet passes through the coils the flux Φ through the coils changes with time as shown in fig 2. The induced emf ε is generated in the coils in the form of two pulses with opposite sign for each swing .The pulse width $\boldsymbol{\tau}$ is the time over which the flux through the coil changes during a swing. The maximum value of ε_o of emf corresponding to the maximum value of

$\left|\frac{d\Phi}{dt}\right|$. This is related to the maximum velocity v_{rms} of the magnet.

I.2. Calculation of v_{rms} :

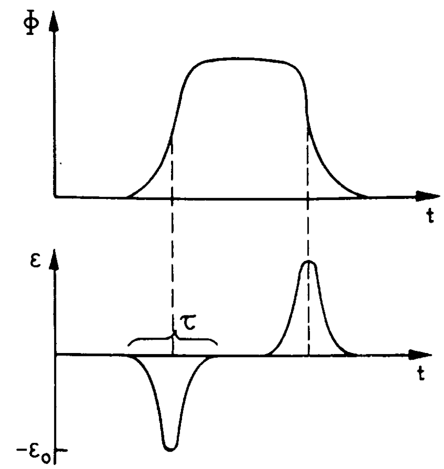


fig 2

The maximum velocity of the magnet is clearly obtained at the equilibrium point i.e. at the bottom of the swing .The velocity v_{rms} can be easily calculated. If M is the mass of the frame and magnet, *l* is the distance of the center of mass from the point of suspension of frame and magnet , and θ_O is the initial release angle , then by conservation of energy, we have

$$\tfrac{1}{2} I \omega^2_{max} = Mg\, l(1-\cos\theta_O) = 2M\, g\, l \sin^2\frac{\theta_O}{2}$$

--------------------(1)

Thus

$$\omega_{max} = 2\sqrt{\frac{M\,g\,l}{I}}\,\sin\frac{\theta_O}{2} \qquad \textbf{----------------(2)}$$

Thus the quantity $\sqrt{\frac{M\,g\,l}{I}}$ is actually the natural frequency of small oscillations .Thus if T is the time period of small oscillations , then

$$T = 2\pi\sqrt{\frac{I}{M\,g\,l}} \qquad \textbf{---(3)}$$

Using eq (3) and $v_{max} = R\,\omega_{max}$ (R is the radius of the arc) we get

$$v_{max} = \frac{4\pi R}{T}\sin\frac{\theta_O}{2} \qquad \textbf{-----------------------------------(4)}$$

I.4. We now give a rough argument that the maximum value of the emf $\varepsilon_{max} = \varepsilon_o$ is proportional to v_{max} .

As the magnet moves, the flux Φ through the coil changes. Clearly $\Phi = \Phi(\theta)$,where θ is the angular position of the magnet . Hence

$$\varepsilon = -\frac{d\Phi}{dt} = -\frac{d\Phi}{d\theta}\frac{d\theta}{dt} = -\frac{d\Phi}{d\theta}\omega \qquad \textbf{-----------------(5)}$$

Thus, ε is also a function of θ, i.e.

$$\varepsilon(\theta) = -\frac{d\Phi(\theta)}{d\theta}\,\omega(\theta) \qquad \textbf{-------------------------------------(6)}$$

At the equilibrium point $\omega = \omega_{max}$ but $\frac{d\Phi}{d\theta} = 0$ hence $\varepsilon_{eq} = 0$. The maximum of the emf

ε_{max} occurs at and angle θ_{max} slightly before the equilibrium point

$$\varepsilon_{max} = \varepsilon_O = -\left.\frac{d\Phi}{d\theta}\right|_{\theta_{max}}\omega(\theta_{max}) \qquad \textbf{---------------------------------------(7)}$$

Since the point θ_{max} is close to the equilibrium $\theta = 0$, $\omega(\theta_{max}) \approx \omega_{max} = \frac{v_{max}}{R}$. Hence

$$\varepsilon_{max} = \varepsilon_O \approx -\frac{1}{R}\frac{d\Phi}{d\theta}\bigg|_{\theta_{max}} v_{max} \quad \text{-------------------------------------(8)}$$

Thus $\varepsilon_o \propto = v_{max}$ approximately and the constant of proportionality depends only on the geometry of the apparatus and is independent of the angle θ_O .Hence a graph of ε_o vs. v_{max} is expected to approximate a straight line.

I.4 In this experiment we will measure ε_o by charging a capacitor by the induced emf .

The capacitor is connected in series with the coil along with a diode and a resistance R. The resistance R_{int} is the internal resistance of the coil and forward resistance of diode and is about 500 Ω .The diode allows current to flow only in one direction and hence the capacitor charges only during one swing of the complete oscillation .If the time constant RC is small compared to the pulse width τ then the capacitor gets fully charged to the maximum voltage ε_o in the swing. However if RC > τ then the capacitor gets fully charged only after several swings .

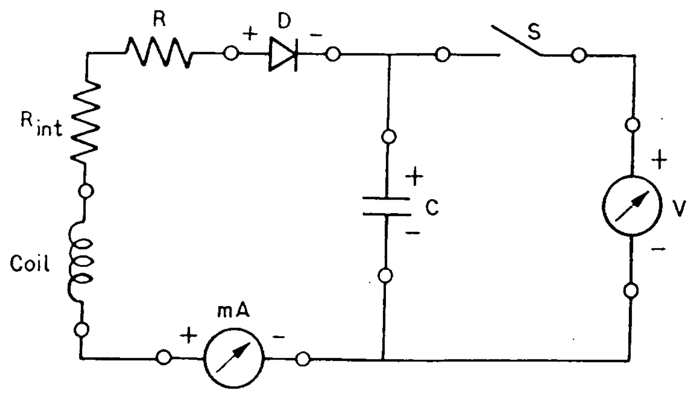


fig 3

The voltage across the capacitor after n swings can be measured by closing the switch S and discharging the capacitor through a voltmeter.

The total charge delivered to the capacitor during each swing is

$$q = \int_{initial}^{final} \frac{\varepsilon\, dt}{R} = -\int_i^f \frac{1}{R}\frac{d\Phi}{dt}dt$$

$$= \frac{1}{R}(\Phi_1 - \Phi_2) = \frac{\Delta\Phi}{R} \quad \text{------------------------------------- (9)}$$

I.5. Electromagnetic damping in an oscillating system

Successive Oscillations of the metal arc do not have the same amplitude . This is due to damping

whose primary sources are i) air friction ii) friction at the point of suspension iii) electromagnetic damping due to Lenz's law .

The damping oscillation of the system can be modeled by the differential equation (assuming small damping)

$$\frac{d^2\theta}{dt^2} + \left(\frac{\omega_O}{Q}\right)\frac{d\theta}{dt} + \omega^2\theta = 0 \quad \text{--------------------------------------(10)}$$

where $\omega_O^2 = \sqrt{\frac{M\,g\,l}{I}}$. The third term arises from the restoring force while the second term proportional to $\frac{d\theta}{dt}$ represents damping . The strength of the damping is characterized by the parameter Q , called the quality factor of the system .Small Q implies large damping, while large values of Q (Q>1) represents small damping . The solution θ(t) to eq (10) can be shown to be oscillatory but with an amplitude which decreases with time as

$$\theta_A(t) = \theta_{AO}\, e^{-\frac{\omega t}{2Q}} \qquad \text{------------------------------------} \ \mathbf{(11)}$$

Thus after n oscillations i.e . $t = nT = n\frac{2\pi}{\omega_O}$ the amplitude decreases from the initial amplitude θ_{AO} by

$$\theta_{An} = \theta_{AO}\, e^{-\frac{\pi n}{Q}} \qquad \text{------------------------------------} \ \mathbf{(12)}$$

Thus $$\ln\theta_{An} = \ln\theta_{AO} - \frac{\pi}{Q} n \qquad \text{--} \ \mathbf{(13)}$$

A plot of ln θ_{An} vs n is expected to be a straight line . The quality factor can be read off from the slope .

II. Setup and Procedure:

Part A: Measurement of time period T for small oscillations

1 Make sure that the equilibrium position of the metal arc + magnet is at $\theta = 0^0$. If not adjust the position of the weights to ensure this.

2. Check that the oscillation of the arc through the coils are free and that the arcs does not touch the sides of the coils when oscillating .

3. Displace the metal arc by a small angle (5^0 - 10^0) and measure the time taken for a few (say5) oscillations .The time period T can be obtained .

Repeat step 3 for different angles.

Part B: Measurement of ε_o .

1. Connect the circuit as in fig 3. Take C = 100 μF and R to be small (~ 100Ω). Connect the two coils in series.

2. Keep the switch in the off position.

3. Choose an initial displacement θ_o (say 40^0) and release the magnet. As the induced current flows in the circuit the millimeter registers kicks. The kicks stop after a few oscillations when the capacitor has become fully discharged.

4. Flip the switch to the ON position and measure ε_o as the maximum voltage recorded by the voltmeter.

5. Repeat for different values of $\theta_o = 40^0, 35^0, 30^0, 25^0, 20^0, 15^0, 10^0$.

6. Calculate v_{max} for each case and plot ε_{o} vs. v_{max} .

Part C: Charge delivered to the capacitor.

1. Choose a large value of R(say 1kΩ) in the circuit of fig 3. The time constant RC is thus greater than $\boldsymbol{\tau}$ ($\boldsymbol{\tau}$ is the approximately estimated by dividing the magnet length by v_{max}).

2. With a given release angle θ_o , measure the voltage V across the capacitor after n complete oscillations , n = 1, 2, 3, ………6.
   (Caution: Each time, i.e. after n oscillations, prevent further oscillations by stopping the frame by hand and measure V.Also make sure that the capacitor is completely discharged each time before making a new measurement) .

3. Repeat for three different values of R.

4. Calculate q = CV for the charge depositing in the capacitor and plot q_n vs. n.

Part D: Electromagnetic damping

1. Let the coils be open. There will be no electromagnetic damping during the oscillations. Give a small (~ 20^0) displacement to the metal arc and measure the amplitude θ_{An} after n swings (n = 1, 2, 3…..)

   Plot ln θ_{An} vs n and calculate the quality Q_0 (without EM damping) .Repeat for another initial displacement.

2. Now connect the coils in series (B to C) and short the ends A & D. Measure for amplitudes θ_{An} (n =1,2,3……) for the same two values of initial displacement as in step 1. Plot ln θ_{An} vs. n (it will be useful to plot all the four graphs on the same graph sheet) and obtain the value of quality Q with electromagnetic damping .
   Note: Since damping is small you may have to take measurement for a large (~ 10) number of swings.

III. Exercises and Viva Questions

1. What is the advantage in having a large number of turns in the coil? What is the effect of connecting the two coils in series or in parallel?

2. Show that the angular frequency for small oscillations of the metal frame is given by $\sqrt{\frac{M\,g\,l}{I}}$

3. What is the effect of moving the weights closer to the point of suspension? Would the emf be the same for the same release angle?

4. Find a way of estimating the angle/ position at which the maximum emf occurs

5. Estimate the pulse width τ for a given θ_0 (from your observation). Would the emf be the same for the same release?

6. The charge deposited per swing (eq 9) appears to be constant (depending only on total change flux and not on the velocity or θo). Does your observation of q depend on θo? If so why?

7. What is the function of the diodes in this experiment? What would happen if the diode were absent in the circuit?

8. Give reasons why the graph ln θ_0 vs n (Part D) could deviate from a straight line?

9. Verify by substitution that $\theta(t) = \theta_0\, e^{-\frac{\omega_0 t}{2Q}} \cos(\omega t + \alpha)$ $\left(\omega = \omega_0 \sqrt{1 - \frac{1}{4Q^2}}\right)$ is a solution of the differential eq(10).

10. Give some practical applications of Faraday's law.

References:

1. "Physics" ,M.Alonso and E.J.Finn, Addison-Wiley, 1992

2. "Introduction to Electrodynamics" , D.J.Griffiths ,PHI, 1998.

Observations and Results

Radius of Arc = 40 cm

Part A (Time period T)

S.No	No. of Oscillations	Time (sec)	T(sec)	Mean T(sec)
1				
2				
3				

Part B : Measurement of ε_0

C= ________________________ μF

θ_0 (degrees)	v_{max} (cm/sec) (calculated)	ε_0
40		
35		
30		
25		
20		
15		
10		

Plot the graph of ε_0 vs v_{max}

Part C : Charge delivered to the capacitor

C = ____________________________ μF

θ_0 = ___________________________

Table I

No.of swings N	R_1 =		R_2 =		R_3 =	
	V	q = CV μ-C	V	q = CV μ-C	V	q = CV μ-C
1						
2						
3						
4						
5						

6						
7						
8						
9						
10						

Plot the graph of q vs n .

Part D : Electromagnetic Damping

Table II

No . of swings	θ_1 = ____________	Amplitude θ_{An}	θ_2 = ____________	
	Without EM damping	With EM damping	Without EM damping	With EM damping
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Plot the graph of $\ln \theta_{An}$ vs n

Discuss briefly how this experiment has verified Faraday’s law .

(Three graph papers required).

Experiment 15

Electrical Resistivity of Semiconductors

Apparatus

Four probe assembly with oven, semiconducting sample, current source, voltmeter etc.

Objective:

To study the temperature variation of electrical resistivity of a semiconducting materials using four-probe technique and determine the bandgap of the semiconductor.

Theory

The Ohm's law in terms of the electric field and current density is given by the relation,

$$\vec{E} = \rho \vec{J} \qquad (1)$$

where ρ is electrical resistivity of the material. For a long thin wire-like geometry of uniform cross-section or for a long parellelopiped shaped sample of uniform cross-section, the resistivity ρ can be measured by measuring the voltage drop across the sample due to passage of known (constant) current through the sample as shown in Fig. 1a . This simple method has following drawbacks:

- The major problem in such method is error due to contact resistance of measuring leads.
- The above method cannot be used for materials having random shapes.
- For some type of materials soldering the test leads would be difficult.
- In case of semiconductors, the heating of samples due to soldering results in injection of impurities into the materials thereby affecting the intrinsic electrical resistivity. Moreover, certain metallic contacts form schottky barrier on semiconductors.

To overcome first two problems, a collinear equidistant four-probe method is used. This method provides the measurement of the resistivity of the specimen having wide variety of shapes but with uniform cross-section. The soldering contacts are replaced by pressure contacts to eliminate the last problem discussed above.

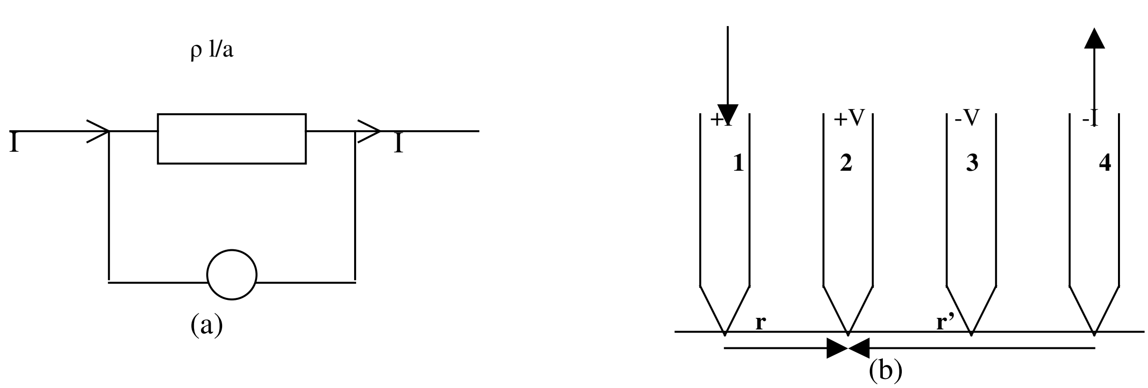


Fig 1

In this method, four pointed**,** collinear equispaced probes are placed on the plane surface of the specimen (Fig.1b). A small pressure is applied using springs to make the electrical contacts. The diameter of the contact (which is assumed to be hemispherical) between each probe and the specimen surface is small compared to the spacing between the probes. Assume that the thickness of the sample d *is* small compared to the spacing between the probes *s (i.e., d << s).* Then the current streamlines inside the sample due to a probe carrying current I will have radial symmetry, so that $\vec{E} = -\left(\frac{\partial V}{\partial r}\right)\hat{r}$ and from eqn.(1),

$$\frac{\partial V}{\partial r}\hat{r} = -\rho\vec{J} \qquad (2)$$

If the outer two probes (l and 4) are current carrying probes, and the inner two probes (2 & 3) are used to monitor the potential difference between the inner two points of contact, then total current density at the probe point '2' which is at a distance **r** from probe '1' and **r'** from probe '4' can be written as,

$$\vec{J} = \frac{I}{2\pi d}\left(\frac{\hat{r}}{r} - \frac{\hat{r}'}{r'}\right) \qquad (3)$$

From eqns. (2) and (3) potential difference between probes (2) and (3) can be written as,

$$V = \frac{I\rho}{2\pi d}\int_{s}^{2s}\left(\frac{1}{r} + \frac{1}{3s-r}\right)dr = \frac{I}{\pi d}\rho\ln 2$$

$$\therefore \quad \rho = \frac{V\pi d}{I\ln 2} \qquad (4)$$

Now temperature variation of resistivity is given by: $\rho = \rho_0\exp(E_g/kT)$, where E_g is the bandgap of the semiconductor. A plot of ln(ρ) vs. 1/T would be a straight line with a slope of E_g/k. Hence bandgap E_g can be determined from the slope of the straight line. For convenience, usually ln(ρ) is plotted as a function of 1000/T (instead of 1/T) and E_g is calculated by taking into account the 1000 factor..

Experimental Set-up:

The four-probe assembly consists of four spring loaded probes arranged in a line with equal spacing between adjacent probes. These probes rest on a metal plate on which thin slices of samples (whose resistivity is to be determined) can be mounted by insulating their bottom surface using a mica sheet. Black leads are provided for carrying current and red leads for voltages measurements. The sample, usually, is brittle, hence do not attempt to mount the sample yourself. This assembly is mounted in a lid of an oven, so that the four probes and the sample can be kept inside the oven and sample can be heated up to a temperature of 200° C. The temperature inside the oven can be measured by inserting a thermometer through a hole in the lid.

The constant current is supplied through probes 1 and 4 by a constant current source. The value of the current can be read from the LED display on the unit. The digital voltmeter is used to measure the voltage drop between probes 2 and 3. It uses the same LED display through a toggle switch. It operates in two modes xl and x10 with maximum of 199.9 mV and 1.999 V, respectively. Oven can be heated to low (L) or high (H) temperatures through the electric supply for it. There is an indicator LED which glows when the oven is turned on

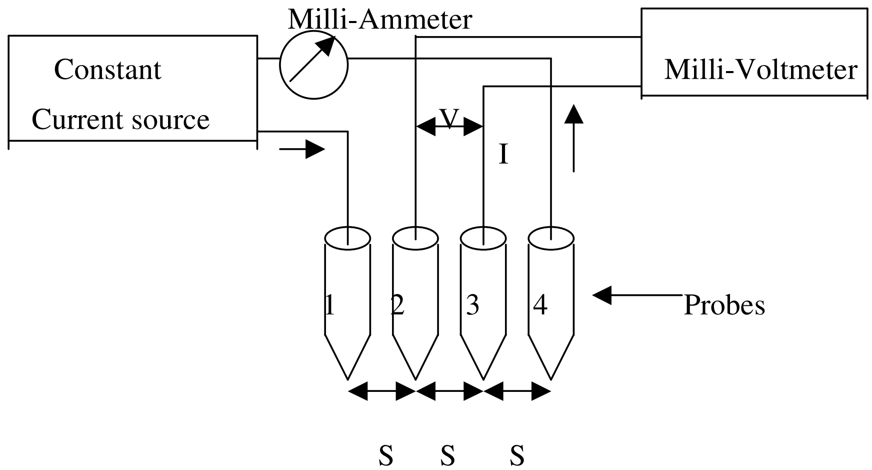


Fig. 2

Procedure:

1. Make the connections as shown in Figure 2.
2. Set some suitable low value of current (2 to 4 mA) from the constant current source. Note down this reading.
3. Switch the LED display to milli-voltmeter mode. Note the temperature and voltage between probes 2 and 3 (V_1).
4. Switch on the oven supply. Record the voltage between the inner probes as a function of temperature using the method described in the previous step.
5. Determine the experimental resistivity as a function of temperature using equation (4) and the measured voltage and current.
6. Express your resistivity data in Ohm-cm unit and temperature in Kelvin**(K). Plot** ln(ρ) vs. 1000/T(K) and see that it is a straight line. From the slope of the line (choose only the linear portion of the curve), calculate E_g (bandgap of the semiconductor) using the relation: $\rho = \rho_0 \exp(\frac{E_g}{2kT})$, where $k = 8.617x10^{-5}$ eV/K.
7. Estimate error in measured resistivity

Observation Table:

Set Current I=

Sl no.	Temperature in C	1000/T(K^{-1})	Voltage (V)	Rsistivity ρ	ln(ρ)

Useful data:
Distance between probes, s=2 mm, Thickness of the sample, d=0.5mm

Calculation:
Plot ln(ρ) vs. 1000/T and use the straight line portion of the graph to calculate the slope of

the straight line. Slope = $E_g/2k*1000$ which yields E_g in eV for the semiconductor material under study.
(One graph paper required)
.
Reference:

D. K. Schroder, "Semiconductor Material and Device Characterization", John Willey & Sons Inc. 1990, Chap 1.

Appendix:

Electrical conductivity of materials

The electrical resistance of matter changes with temperature. The number of quasi-free electrons increases with rising temperature which causes the current to increase and the resistance to decrease. On the other hand, the ions of the crystal lattice oscillate more strongly with increasing temperature, thus hindering the electron movement, so that the current decreases and the resistance increases.

In conductors (e.g. metals such as Cu, Ag, Al) the second effect dominates, since at room temperature nearly all conduction electrons are quasi-free and contribute to the electron gas. A rise in temperature does not considerably influence their number, so the resistance of metals increases with temperature. Generally this is only a small effect, which can be the other way round in some special alloys!

In semiconductors and isolators the first effect dominates, as a rise in temperature can increase the number of quasi-free electrons considerably: Due to the stronger atomic binding only few quasi-free electrons exist at room temperature. Rising temperature thus leads to a decrease of the electrical resistance. Electrical conductors show an approximately linear dependence between temperature and resistance. Let R_0 and R_t be the resistances at temperatures t_0 and t_1 respectively. Then

$$R_t = R_0(1+\beta(t_1 - t_0)) \quad (1)$$

The temperature coefficient β characterizes the relative change in resistance per 1 °C or K.

Semiconductors show an approximately exponential temperature dependence:

$$R(T) = a \cdot e^{\frac{b}{T}} \quad (2)$$

, where a and b are empirical constants.

Table 1: Data of typical materials used for resistors.

Material	**Resistivity ρ at 20°C /Ωm**	**Temperature coefficient α at 20°C / K^{-1}**
Silver	$1.6 \cdot 10^{-8}$	$3.8 \cdot 10^{-3}$
Copper	$1.7 \cdot 10^{-8}$	$3.9 \cdot 10^{-3}$
Aluminum	$2.8 \cdot 10^{-8}$	$3.9 \cdot 10^{-3}$
Iron	$10 \cdot 10^{-8}$	$5.0 \cdot 10^{-3}$
Mercury	$96 \cdot 10^{-8}$	$0.9 \cdot 10^{-3}$
Nichrome	$100 \cdot 10^{-8}$	$0.4 \cdot 10^{-3}$
Carbon	$3500 \cdot 10^{-8}$	$- 0.5 \cdot 10^{-3}$
Silicon	640	$- 7.5 \cdot 10^{-2}$

Experiment 16

Planck's constant

Apparatus:

Photoelectric cell, DC source, DC millimeter, Variac (AC) (0-260V), AC ammeter, Tungsten filament lamp (60 W), Monochromatic filters.

Purpose of experiment:

To measure the value of Planck's constant 'h'.

Basic methodology:

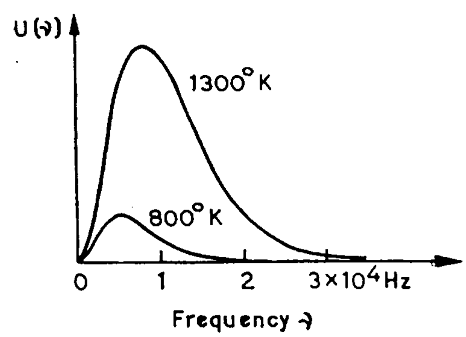
Light from a tungsten filament lamp (assumed to be a black body source) is passed through a
Monochromatic filter and made to fall on a photoelectric cell. The slope of the graph ln I_{ph} vs. $\frac{1}{T}$, leads to a determination of Planck's constant.

I Introduction:

I.1 The electromagnetic radiation emitted by a black body (a perfect absorber and emitter of electromagnetic radiation) is spread continuously over the entire electromagnetic spectrum. It was Planck who first gave the law for black body radiation based on the idea that electromagnetic radiation is composed of quanta called photon of energy
$\varepsilon = h\nu$, where ν is the frequency of radiation and h is Planck's constant.

I.2 Planck's law for radiation from a black body gives the energy of the radiation in the frequency range ν to $\nu + d\nu$. This is denoted as $U(\nu)\, d\nu$ and is given by

$$U(\nu)\,d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{\left(e^{\frac{h\nu}{kT}} - 1\right)}d\nu \quad \textbf{--------(1)}$$



In eq. (1), $c = 3 \text{ X } 10^8$ m/s is the speed of light, $K = 1.38 \text{ X } 10^{-23}$ J/K is the Boltzman Constant. Fig. 1 shows a graph of $U(\nu)$ vs. ν for given temperature T.

In the high frequency region, where $\frac{h\nu}{kT} >> 1$, eq. (1) can be approximated as

$$U(\nu) = \frac{8\pi h\nu^3}{c^3}e^{-\frac{h\nu}{kT}} \quad \textbf{----------------------------(2)}$$

Showing an exponential decrease in the energy density with frequency.

I.3 In this experiment, a tungsten filament lamp is taken to be a black body radiator. Using a monochromatic filter, radiation with frequency in the visible region is selected. For the range of temperatures of the tungsten filament, the energy density can be taken to be given by eq. (2). The energy density at the chosen frequency is indirectly measured by measuring the photocurrent I_{ph} generated upon exposing a photocell to the radiation. From the properties of the photoelectric effect, it is known that the photocurrent is proportional to the intensity of the radiation. Thus

$$I_{ph} \propto U(\nu) \approx \frac{8\pi h\nu^3}{c^3} e^{-\frac{h\nu}{kT}} \qquad \textbf{------------------------------------ (3)}$$

or $$\ln I_{ph} = -\frac{h\nu}{kT} + \ln\frac{8\pi h\nu^3}{c^3} = -\frac{h\nu}{kT} + \text{constant} \qquad \textbf{------------------(4)}$$

Hence the graph of $\ln I_{ph}$ Vs $1/T$ will be a straight line of slope of magnitude $h\nu/K$.

I.4 The temperature of the tungsten filament can be varied by changing the current through it. The temperature of the filament can be estimated by measuring the resistance R of the filament. The variation of R with temperature for tungsten is given by the empirical formula (T is expressed in ^oC)

$$R = R_o (1 + \alpha T + \beta T^2) \qquad \textbf{----------------------------(5)}$$

Where

R_{34oC} = Resistance at 34^oC = 57Ω and 64Ω for set 1 and set 2

$\alpha = 5.24 \times 10^{-3} (^oC)^{-1}$

$\beta = 0.7. \times 10^{-6} (^oC)^{-2}$

A calibration graph can be obtained by drawing the graph of eq. (5).Then, knowing the resistance R = V/I of the filament the temperature T (^oC) can be obtained from the calibration graph.

II. Set-up and Procedure

1. Complete the circuit with Tungsten lamp and photocell as shown in Fig. (2)

2. Choose and set the colour of the monochromatic filter (say red).

3. Using the variac, vary the AC voltage to the tungsten filament from 80V to 220V
   In steps of 20V.

4. Measure the AC current to the tungsten and the DC photocurrent I_{ph}.

5. Repeat the measurements for three filters in all (say red, blue and green).

6. Prepare the calibration graph of R (resistance of filament) by using eq. (5) to calculate R for value of T (^oC) = 400, 600, 800, 1000 …2000.
   Plot and find the calculated value of R vs. T by a best fit straight line.

7. Calculate the resistance R = V/I from your measurement and use the calibration graph to read off temperature of the filament, against the value of the resistance

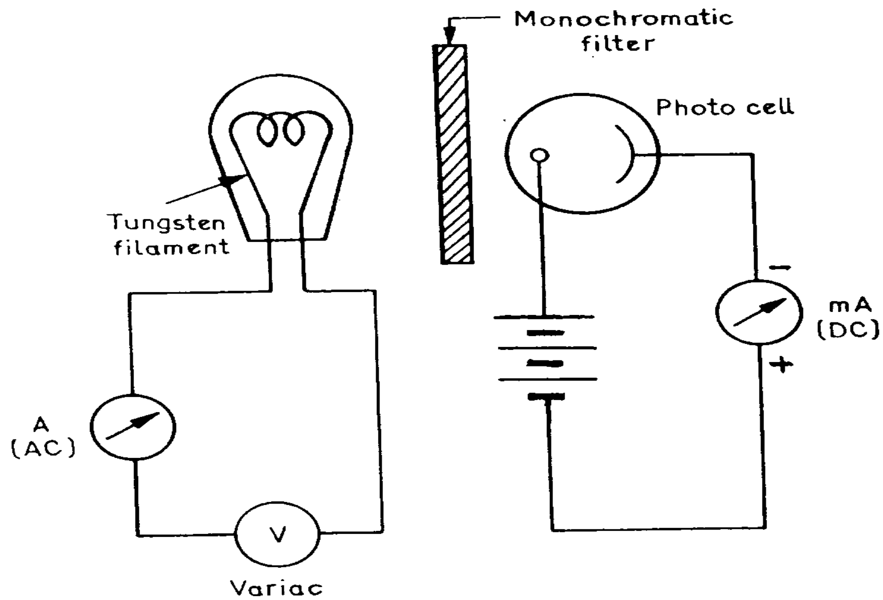


Fig. 2

III. Exercise and Viva Questions:

1. What is the meaning of the quantity $U(\nu)$ in the Planck's black body radiation law?

2. Give the approximate form of the energy density for $(h\nu /KT) << 1$ and $(h\nu /KT) >> 1$.

3. What is the purpose of using a photocell in this experiment?

4. Use the energy density expression to argue how the photocurrent should change upon varying the frequency, keeping the variac voltage same. How will I_{ph} change if the frequency is kept constant but the variac voltage is varied? Verify your expectations from your observations.

5. Argue how I_{ph} would change as the variac voltage is changed if the tungsten lamp were allowed to illuminate the photocell without using a filter in-between. What frequency would contribute most to the photocurrent?

6. Study the photoelectric effect and list the characteristics of the photoelectric effect which can only be explained by the quantum nature of light.

7. Is our assumption that I_{ph} $U(\nu)$ always right ? Is it true that radiation of any frequency will give rise to a photocurrent?

8. Look up the value of work function of tungsten and calculate the cut off frequency ν_o for tungsten.

9. We have taken the tungsten filament to be a black body radiator. What qualitative change would we expect if it were taken to be an imperfect black body?

10. What is the significance of the Planck's constant in physics?

References:

1. "Physics", M. Alonso and J. Finn, Addison Wesley 1992.

2. "Modern Physics ", A. Beiser, McGraw Hill Inc., 1995.

Experiment 16

Planck's constant

Observations and Results

1. Calibration of R Vs T : R_o (calculated) = ______________________ Ω

Table 1.

T (^oC)	R(Ω)

Plot a graph of R Vs T and fit a straight line.

2. Verification of photocurrent (I_{ph}) with variac voltage (V)

Table 2.

Variac Voltage (V)	Photocurrent					
	I_{ph} (mA)			ln I_{ph}		
	Filter 1 ν =______	Filter 2 ν =______	Filter 3 ν =______	Filter 1 ν =______	Filter 2 ν =______	Filter 3 ν =______
80						
100						
120						
140						
160						
180						
200						
220						

3. Calculation of temperature (T) of filament

Table 3.

Variac Volatage(V)	Filament Current I (A)	Resistance R = V/I (Ω)	T (^oC) Calculated	T (K)	1/T (K^{-1})
80					
100					
120					
140					
160					
180					
200					
220					

4. Plot graphs of ln I_{ph} Vs 1/T (K^{-1}) for the three filter colours.

5. Calculate the Planck's constant from the slope of the graphs.

Calculation:

Results:

The measured value of Planck's constant h = ________________________

The known value of Planck's constant h = ________________________

% error in the experiment:

Experiment 17

Study of magnetic field along the axis of a coil

Apparatus:
Circular coil, power supply, switching keys, magnetic needle, sliding compass box etc.

Objective
To measure the magnetic field along the axis of a circular coil and verify Biot-Savart law.

Theory

For a circular coil of a n turns, carrying a current I, the magnetic field at a distance x from the coil and along the axis of the coil is given by

$$B(x) = \frac{\mu_0 n I R^2}{2} \frac{1}{\left(R^2 + x^2\right)^{3/2}} \qquad (1)$$

where R is the radius of the coil.

In this experiment, the coil is oriented such that the plane of the coil is vertical and parallel to the north-south direction. The axis of the coil is parallel to the east-west direction . The net field at any point x along the axis, is the vector sum of the fields due to the coil B(x) and earth's magnetic field B_E (Fig 1).

$$\therefore \tan\theta = \frac{B(x)}{B_E}$$

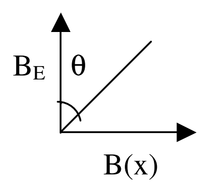


Fig 1.

Procedure

The appratus consists of a coil mounted perpendicular to the base. A sliding compus box is mounted on aluminium rails so that the compus is always on the axis of the coil.

1. Orient the apparatus such that the coil is in the north-south plane.
2. Adjust the levelling screws to make the base horizontal . Make sure that the compus is moving freely.
3. Connect the circuit as shown in the figure.
4. Keep the compus at the center of the coil and adjust so that the pointers indicate 0-0.
5. Close the keys K and KR (make sure that you are not shorting the power supply) and adjust the current with rheostat, RH so that the deflection is between 50 to 60 degrees. The current will be kept fixed at this value for the rest of the experiment.
6. Note down tha readings θ_1 *and* θ_2 . Reverse the current and note down θ_3 *and* θ_4

.7. Repeat the experiment at intervals of 1cm along the axis until the value of the field drops to 10% of its value at the center of the coil. Repeat on both sides of the coil.
8. Draw following graphs:

. **B(x)** as a function of x.

. log(B(x)) as a function of $\log\left(R^2 + x^2\right)$

Find slope and y-intercept from the graph and verify results with the expression for B(x).

Observations/Calculations

Parameters and constants

- Least count for *x* measurement=
- Least count for θ measurement=
- No of turns of the coil,n=..
- Radius of the coil,R=10cm
- Current in the coil,I=....
- Permeability of air, $\mu_0 = 4\pi \times 10^{-7}$ N/A^2
- Earth's magnetic field, $B_E = 0.39\times10^{-4}$ T

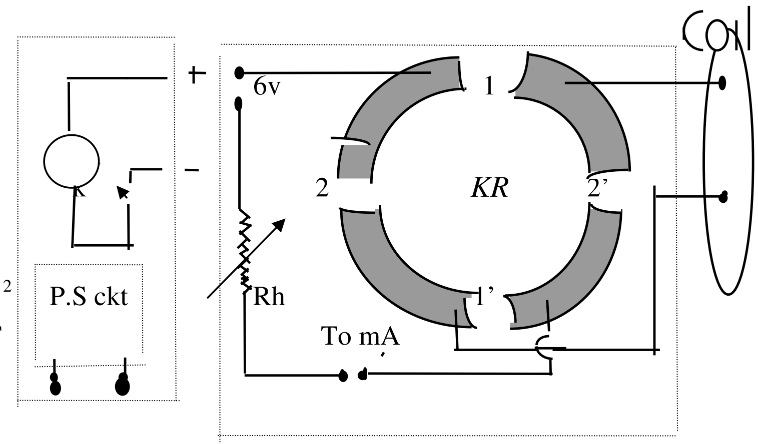


Fig 2.

Observations

i. Least count of x-measurement= …
ii. Least count for θ measurement = …
iii. No. of turns of the coil (n) = …
iv. Radius of the coil = …
v. Current in the coil = …..A
vi. Permeability of air (μ_o) = $4\pi\times10^{-7}$ N/A^2
vii. Earth's magnetic field $B_E = 0.39\times10^{-4}$ Tesla.

Table I

X (cm)	θ_1	θ_2	θ_3	θ_4	θ *(average)*	Tan θ	log(tanθ)	log($R^2 + x^2$)	B(x)= B_E tanθ (T) (10^{-4})	Log B(x)
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
…										
….										

Table II

For other side of the scale ……

X (cm)	θ_1	θ_2	θ_3	θ_4	θ *(average)*	Tan θ	log(tanθ)	log($R^2 + x^2$)	B(x)= B_E tanθ (T) (10^{-4})	Log B(x)
1										
2										
3										
4										

5										
6										
7										
8										
9										
10										
11										
…										
….										

Calculation:

From the graph of B(x) vs. log (R^2+x^2), find the slope and intercept from regression analysis. Slope should be -1.5 according to Biot-Savart law, and intercept value should match with the value calculated using μ_o, n, I, and R.

Results:

Experimental value of exponent (slope) = ….

Theoretical value of slope = -1.5

Experimental value of intercept = ….

Theoretical value of intercept = ….

(Two graph papers required).

References: David J. Griffiths, "Introduction to Electrodynamics", Prentice Hall, 2000, *Chap. 5*.

Experiment 18

Study of Hall Effect

Apparatus

Commercial setup with the following components: electromagnet with power supply, Hall probe, Semiconductor sample, arrangement for pressure contact, current supply with meter, voltmeter etc.

Objective:

To study Hall effect in extrinsic semiconducting samples and determine the type and density of majority charge carriers. This experiment demonstrates the effect of Lorentz force.

Introduction:

Consider a rectangular slab of semiconductor with thickness *d* kept in XY plane [see Fig. 1(a)]. An electric field is applied in *x*-direction so that a current *I* flows through the sample. If *w* is width of the sample and *d* is the thickness, the current density is given by $J_x=I/wd$.

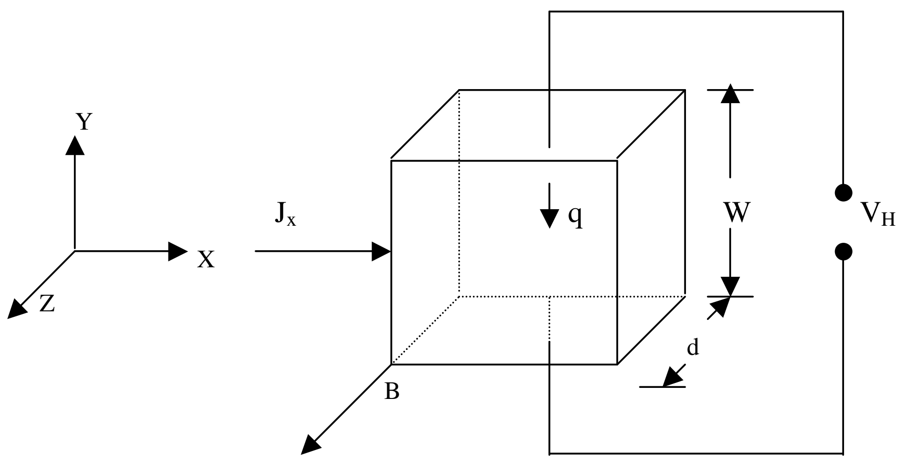


Fig. 1

Now a magnetic field *B* is applied along positive z axis (fig. 1). If the charge carriers are positive (negative) and are moving with velocity v along positive (negative) x-axis then the direction of force experienced by the charge carriers in presence of magnetic field is along negative y direction. This results in accumulation of charge carriers towards bottom edge (fig1.). This sets up a transverse electric field E_y in the sample. The potential, thus developed , along y-axis is known as Hall voltage V_H and this effect is called Hall effect. Assuming E_y to be uniform the Hall voltage is given by

$$V_H = E_y w \qquad (1)$$

and the hall coefficient R_H is given by

$$R_H = \frac{E_y}{J_x B} = \frac{V_H d}{IB} \qquad (2)$$

The majority carrier density *n* is related to the Hall coefficient by the relation

$$R_H = \frac{1}{qn} \tag{3}$$

where q is the charge.

From Equation (3), it is clear that the sign of charge carrier and density can be estimated from the *sign and value of Hall coefficient R_H*. R_H can be obtained by studying variation of V_H as a function of I for given B.

Experimental Set-up

Sample is mounted on a sunmica sheet with four spring type pressure contacts. A pair of green colour leads are provided for current and that of red colour for hall voltage measurement. Note the direction of current and voltage measurement carefully. **Do not exceed current beyond 10 mA**.

The unit marked "Hall Effect Set-up" consists of a constant current generator (CCG) for supplying current to the sample and a digital milli voltmeter to measure the Hall voltage. The unit has a digital display used for both current and Hall voltage measurement.

For applying the magnetic field an electromagnet with a constant current supply is provided. It is capable of generating a magnetic field of 7.5 Kgauss between its pole pieces. The magnetic field can be measured by gauss meter along with the hall probe based on the Hall effect.

Procedure

1. Connect the leads from the sample to the "Hall effect Set-up" unit. Connect the electromagnet to constant current generator.
2. Switch on the current through sample and measure the hall voltage without any magnetic field. There may be some voltage due to misalignment of pressure contacts on the sample. This error must be subtracted from the readings.
3. Switch on the electromagnet and set suitable magnetic field (<3 Kgauss). You can measure this using Hall probe. (Set magnetic field B=2 kG and B=3 kG for the experiment).
4. Insert the sample between the pole pieces of the electromagnet such that I, B and V are in proper direction (Fig.1).
5. Record the hall voltage. Also record voltage by reversing both the current and magnetic field simultaneously. *(Note down data for the first two columns with +B for all I's and then reverse the field (-B) to record data for the next two columns)*
6. Keeping the magnitude of magnetic field constant, measure hall voltage as a function of I.
7. Repeat step 5 and 6 for various magnetic fields.

Plot V_H as a function of I using the averaged data and find the value of Hall coefficient from the slope of the graph. Hence determine charge carrier density and type of majority carrier in the given material.

Note down the sample number or details of the sample.

Observation Table:

Sample number: *Thickness of the sample:* ***Magnetic field: B= 2000 Gauss***

Sl. No.	I (mA)	V_{H1}(+I,+B)	V_{H2}(-I,+B)	V_{H3}(+I,-B)	V_{H4}(-I,-B)	$V_{H\ avg}$
1	1					
2	2					
3	3					
4	4					
5	5					
6	6					
7	7					
8	8					

Magnetic field: B= 3000 Gauss

Sl. No.	I (mA)	V_{H1}(+I,+B)	V_{H2}(-I,+B)	V_{H3}(+I,-B)	V_{H4}(-I,-B)	$V_{H\ avg}$
1	1					
2	2					
3	3					
4	4					
5	5					
6	6					
7	7					
8	8					

Plot two graphs and from the slope, calculate Hall coefficient R_H.

From the sign of the Hall voltage with the given current and field direction, determine the type of conductivity in the semiconductor material.

Calculate free carrier density (n) = $1/(q\ R_H)$ = …. m^{-3}

Results:

For the given sample, R_H = ……..
n = …….
Type of majority carrier = ……

(Two graph papers required).

Reference: D. K. Schroder, "Semiconductor Material and Device Characterization", John Willey & Sons Inc. 1990, *Chap 5*

Experiment 19

I-V Characteristic of Solar Cell

Apparatus:
Solar cell, rheostat, ammeter, voltmeter, illumination source, varic and connecting wires.

Purpose of experiment:
To study illuminated characteristics of a solar cell for different illumination levels.

Basic methodology:
A solar cell is illuminated by light having photon energy greater than the band gap energy of the solar cell. Then, using a proper circuit, the open circuit voltage, short circuit current and power drawn from the solar cell are measured.

I. Introduction

I.1 Solar cell is basically a two terminal p-n junction device designed to absorb photon absorption through the electrical signal or power in the external circuits. Therefore it is necessary to discuss the physics of semiconductor p-n junction diode, which converts the optical energy into electrical signals.

I.2 It is well known that doped semiconductors are of two types, p and n- types semiconductors depending upon the nature of the charge carriers. In n-type semiconductor the free carriers are electrons and in p-type semiconductor, the positive charge carriers are holes. Since the semiconductors are electrically neutral, in a doped semiconductor the number of free carriers is equal to the lattice ions present in the semiconductor. The nature of the semiconductor can be defined from the location of Fermi energy level (E_F) in the band structure of the semiconductor as shown in Fig.1. (The Fermi energy level is defined as the highest filled energy level at 0 K). In p-type semiconductor the Fermi level lies just above the valence band (E_V) and in n-type semiconductor it lies just below the conduction band (E_C) as shown in Fig. 1. When these two types of semiconductors come in contact, the free carriers flow in opposite direction and neutralize each other. This process will continue until the Fermi energy levels of the two semiconductors come to the same level as shown in Fig. 2.

The region surrounding the junction thus only contains the uncovered positive ions in n-side and uncovered negative ions in p-side. This region is known as the depletion region (W) and there are no free carriers available in this region (Figure 3a). In the depletion region, the nature of Fermi energy level is most important from device point of view.

The variation of different parameters across the depletion region are also shown in Fig. 3(b-e).

________________________ E_C __________________________ E_C
                                                  ------------------------------------ E_F

------------------------------- E_F
________________________ E_V __________________________ E_V

p-type semiconductor n-type semiconductor

Figure 1. Location of Fermi energy level in p and n type semiconductors.

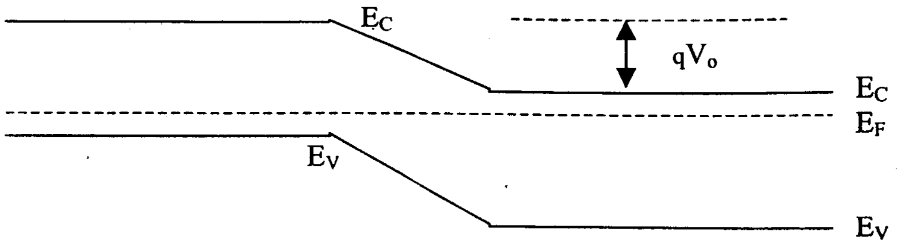


Figure 2. Energy bend band diagram of p-n junction diode under no bias condition. V_o is the potential difference at the depletion region.

I.3 A p-n junction semiconductor can be used in forward as well as in the reverse biasing mode. If V is the applied reverse voltage across the junction then the current in the external circuit can be expressed as follows:

$$\mathbf{I = qA\left[\left(\frac{L_p}{\tau_p}\right)p_n + \left(\frac{L_n}{\tau_n}\right)n_p\right]\left(e^{\frac{qV}{kT}} - 1\right)} \qquad (1)$$

Where,

$L_{p,n}$ = Recombination length of holes and electrons in semiconductors.

$\tau_{p,n}$ = Life time of holes and electrons.

A = Surface area of the junction in p-n semiconductor diode.

p_n , n_p = minority carrier density in n and p sides.

V = is the applied reverse bias voltage across the junction.

For a combination of two particular semiconductors, the quantity

$$\mathbf{qA\left[\left(\frac{L_p}{\tau_p}\right)p_n + \left(\frac{L_n}{\tau_n}\right)n_p\right] = Constant = I_{rs}}\ .$$

and is known as the reverse saturation current (I_{rs}).

I.4 When a radiation of photon energy greater than the band gap energy of the semiconductor falls up on the surface across the junction (i.e., region surrounding the depletion region), it produces new electron – hole (e-h) pairs. Since there exists a junction potential difference as shown in Fig 3, the new carriers flow in opposite directions depending on their nature of charge. Under this condition eq. (1) can be modified as follows:

$$I = qA\left[\left(\frac{L_p}{\tau_p}\right)p_n + \left(\frac{L_n}{\tau_n}\right)n_p\right]\left(e^{\frac{qV}{kT}} - 1\right) - Aqg_{op}\left(L_p + L_n\right) \tag{2}$$

Where, g_{op} is the optical generation rate of e-h pairs per (cm^3- sec) and V is the applied

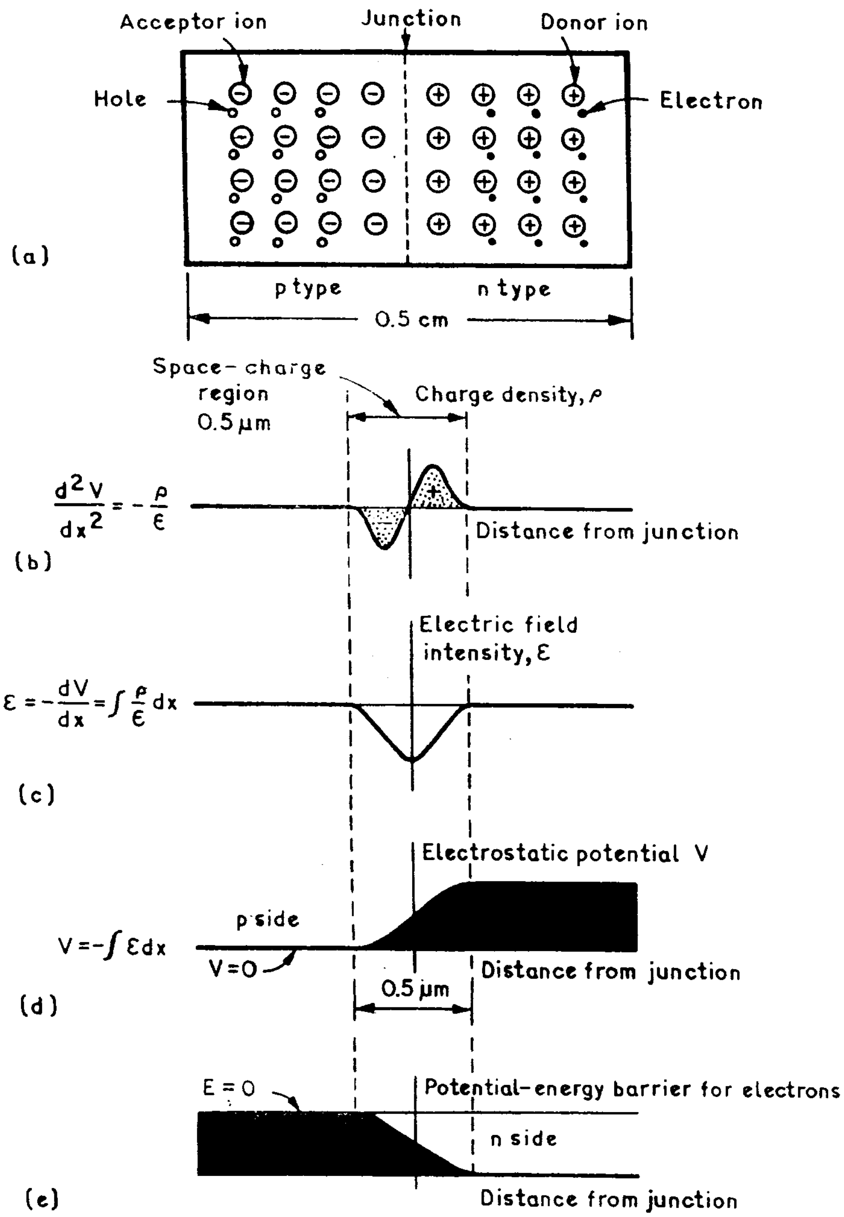


Figure 3. Schematic diagram of p-n junction showing different parameters exist across the junction [Taken from reference 2].

reverse bias across the p-n junction diode. The second part of the equation is the current due to optical generation of e-h pairs (I_{op}). So, the above equation could be written as

$$\mathbf{I} = \mathbf{I}_{rs}\left\{\left(e^{\frac{qV}{kT}}\right) - 1\right\} - \mathbf{I}_{op} \qquad (3)$$

Following eq.(2), when the device is short circuited (V=0), there is a short – circuit current from p to n equal to I_{op}. The usual (i.e., under dark conditions) V-I characteristic for diode is shown in Fig. 4 by the dashed line that passes through the origin (see eq. (1)).

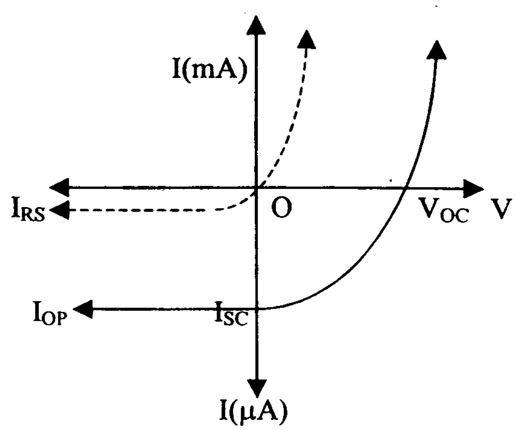


Figure 4. V-I characteristic curves of a photo-diode under dark (------) and illuminated
(___) conditions.

When the optical generation current, I_{op} is introduced , the nature of the characteristic curve is modified. In the illuminated condition, the curve passes through the fourth quadrant also. When the circuit is open, I=0, using applied reverse bias is also zero, the potential across the junction due to optical generation of electron – hole pairs, become V_{oc} (as like V) and one can write from eq. (2),

$$\mathbf{V}_{oc} = \left(\frac{\mathbf{kT}}{\mathbf{q}}\right)\mathbf{ln}\left[\frac{(\mathbf{L}_p + \mathbf{L}_n)\mathbf{g}_{op}}{\left\{\left(\frac{\mathbf{L}_p}{\tau_p}\right)\mathbf{p}_n + \left(\frac{\mathbf{L}_n}{\tau_n}\right)\mathbf{n}_p\right\}} + 1\right] \qquad (4)$$

Under this condition the Fermi levels will again change the nature in depletion region. From the difference of the Fermi levels in n and p-type semiconductors one can express the open circuited voltage as shown in Fig . 5.

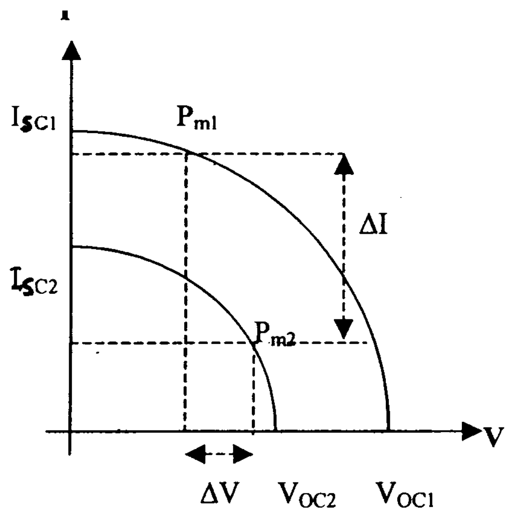


Figure 5. Illuminated I-V characteristics for solar cell for two different illuminations

I.5 When we need to use the photodiode as detector application, we usually operate it in the 3rd quadrant. If power is to be extracted from the device, the fourth quadrant is used. The equivalent circuit for the purpose is shown in Fig. 6. in the experimental section. The maximum power delivered through the load R_L is when the series resistance R_S is equivalent to the value of R_L as given in the procedure. Again to receive maximum power from solar cell, it is designed with large surface area coated with appropriate materials to reduce the reflection of the incident light and to reduce the recombination. Therefore in solar cell device the junction depth from the surface must be less than the recombination length of electron and holes from both sides, so that the optically generated carriers can reach the depletion region before recombination with the majority carriers in the semiconductors. In most of the cases the incident photons penetrate the n and p regions and are absorbed in the depletion region.

II. Set-up and procedure:

1. Complete the circuit as shown in circuit diagram (figure 6.)

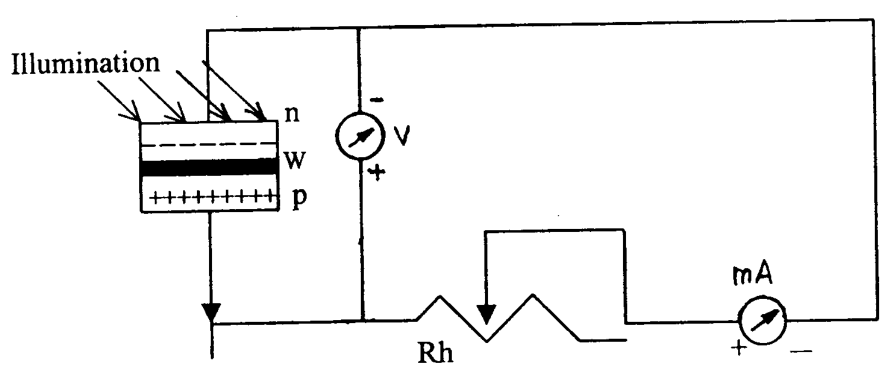


Figure 6. Circuit diagram of performing the solar cell experiment

2. Illuminate the solar cell. Adjust the rheostat position for resistance so that the volt meter reads zero. This is the short circuit connection. Adjust the variac

(maximum up to 230 V) such that ammeter reads a value of about 500 mA. Note down the value of the current as short circuited current, I_{sc} .

3. Increase the resistance by varying the rheostat slowly and note down the readings of current and voltage till a maximum voltage is read. Ensure to take at least 15 – 20 readings in this region.

4. Disconnect he rheostat and note down the voltage. This is the open circuit voltage, V_{oc}.

5. Repeat the experiment for another intensity of the illumination source.

6. Tabulate all readings in Table 1. Calculate the power using the relation, P = V x I.

7. Plot I vs. V with I_{sc} on the current axis at the zero volt position and Voc on the voltage axis at the zero current (see Figure 5.)

8. Identify the maximum power point P_m on each plot. Calculate the series resistance of the solar cell using the formula as follows : $R_S = [\ \Delta V/\Delta I\ ]$.
9. To see the performance of the cell calculate fill factor (FT) of the cell, which can be expressed by the formula, FF = [P_m/Isc Voc].

III. Exercise and Viva Questions:

1. What is a semiconductor? What are p and n type semiconductors? Give one example of each.

2. What are the advantages of using doped semiconductor rather than pure semiconductors? Why are semiconductor diodes preferred to valve diodes?

3. What is the meaning of valence and conduction band in semiconductor? How is the
Fermi energy level in a semiconductor defined?

4. Why do the Fermi energy levels come to the same level when p and n-types of semiconductors come in contact?

5. What is the depletion region? Assuming majority carrier concentration in n-type semiconductor is higher than p-type, discuss about the width of the depletion region about the physical contact layer.

6. What is the meaning of recombination, recombination length, and life time of carriers in doped semiconductor?

7. What is reverse saturation current in p-n diode? If you increase the reverse bias voltage, what will be the nature of the 3rd quadrant part of the dotted line in figure 4?

8. Try to deduce equation 4 from equation 2 under proper assumption.

9. Discuss the curve in the 4^{th} quadrant of Fig 4.

10. Give some practical uses of the solar cell.

References:

1. "Solid State Electronics Devices " , B.G.Streetman, Prentice-Hall of India Private Limited, Third Edition, 1993.

2. "Integrated Electronics " , J.Millman and C.C.Halkias, McGraw-Hill Kogakusha Ltd., International Student Edition.

Experiment 19
I-V Characteristic of Solar Cell

Observations and Results

Table 1

S.No.	Illumination 1 : Variac Voltage			Illumination 2 : Variac Voltage		
	Volts (mV)	Current (mA)	Power (mW)	Volts (mV)	Current (mA)	Power (mW)

Calculations :

1. Fill up Table 1 and identify the maximum power point for both illumination levels [P_{m1} and P_{m2}]

2. Plot I vs. V for both illumination levels.

3. Mark P_{m1} and P_{m2} on the plots.

4. Note down V and I (as in Fig. 5).

5. Calculate the series resistance and fill factor.

Results:

1. The I-V characteristic was drawn for given solar cell for two illumination levels.

2. The open circuit voltages and short circuit currents for two different illuminations are measured as :
   V_{oc1} = ____________;V_{oc2} = _____________;

   I_{sc1} = ______________ and I_{sc2} = _____________

3. The series resistance of the cell calculated using the two plots is ________________________.

4. Fill factor :

(One graph paper required).

Experiment 20

Air wedge: Interference of light

Apparatus

Glass plate, thin wire, beam splitter, light source, traveling microscope etc.

Objective:

To measure the diameter of a given thin wire using interference patterns formed using an extended source, at the air wedge between two glass plates.

Theory:

Interference effects are observed in a region of space where two or more coherent waves are superimposed. Depending on the phase difference, the effect of superposition is to produce variation in intensities which vary from a maximum of $(a_1 + a_2)^2$ to a minimum of $(a_1 - a_2)^2$ where a_1 and a_2 are amplitude of individual waves. For the interference effects to be observed, the two waves should be coherent. Interference patterns can be observed due to reflected waves from the top and bottom surfaces of a thin film medium. Because of the extended source, the fringes are localized at or near the wedge.

Fig (1) shows the cross sectional view of the two flat glass plates kept on each other and separated by a wire at the rightmost end. There is a thin air film between the two glass plates due to the wire kept at the right end.

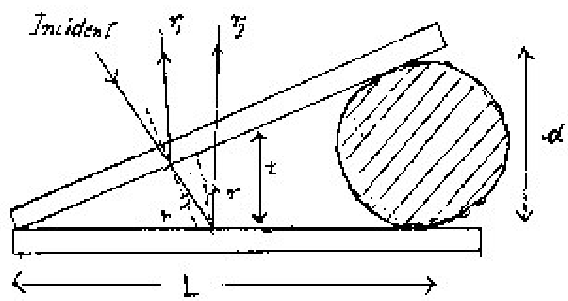


Fig. 1 Air Wedge

The path difference between the two rays r_1 and r_2 is $2t\cos r$, where '*t*' is the air thickness as shown in the figure

The condition for dark band is,

$$2t\cos r = m\lambda$$

If the incident ray is close to normal ,

$$2t = m\lambda \qquad (1)$$

For m=N, the maximum order of the dark band the path difference will be maximum and this correspond to the position where the wire is kept .Moreover, here the fringes are equal thickness fringes. So Eqn (1) can be written as

$$2d = N\lambda \qquad (2)$$

The length 'L' shown in the figure can be written as

$$L = N\beta \qquad (3)$$

where β is the fringe width. From eq (2) and (3),

$$d = L\lambda/2\beta \text{----------------------------}(4)$$

Procedure:

1. Place the two optically flat glass plates one over the other , so that they touch each other at the left end and are separated at the right end by the given thin wire . The length of the wire should be perpendicular to the length of the glass plate.

2. Place this assembly on the platform of the microscope such that the length of the glass plate is parallel to the horizontal traverse of the microscope.

3. Illuminate the assembly by sodium light. Adjust the glass plate G, such that incident light is almost normal to the glass plate wire assembly.

4. Focus the microscope to observe the interference patterns

5. Measure the horizontal positions of the dark bands in the order of say, m, m+5, m+10,......... by traversing the microscope horizontally.

6. Determine the length 'L' with the help of microscope.

7. Plot a graph of horizontal positions versus order of dark band. Find out the mean fringe width β from the graph and calculate the thickness of the given wire.

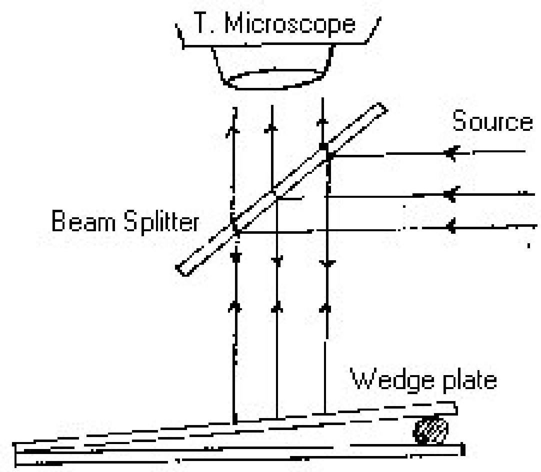


Fig. 2 Experimental setup

Results:
Thickness of the wire = ………………….

(One graph paper required).

Wavelength of the source: 5893 A

References:

1. F. A. Jenkins and H. F. White, "Fundamentals of Optics" (McGraw Hill, 1981), *Chapter 14*.
2. E. Hecht and A. Zajac, "Optics", (Addision Wesley, 2nd Ed. 1987).

Experiment 21

Newton's Rings

Apparatus:

Traveling microscope, sodium vapour lamp, plano-convex lens, plane glass plate, magnifying lens.

Purpose of the experiment:

To observe Newton rings formed by the interface of produced by a thin air film and to determine the radius of curvature of a plano-convex lens.

Basic Methodology:

A thin wedge shaped air film is created by placing a plano-convex lens on a flat glass plate. A monochromatic beam of light is made to fall at almost normal incidence on the arrangement. Ring like interference fringes are observed in the reflected light. The diameters of the rings are measured.

I. Introduction:

I.1 The phenomenon of Newton's rings is an illustration of the interference of light waves reflected from the opposite surfaces of a thin film of variable thickness. The two interfering beams, derived from a monochromatic source satisfy the coherence condition for interference. Ring shaped fringes are produced by the air film existing between a convex surface of a long focus plano-convex lens and a plane of glass plate.

I.2. Basic Theory:

When a plano-convex lens (L) of long focal length is placed on a plane glass plate (G) , a thin film of air I enclosed between the lower surface of the lens and upper surface of the glass plate.(see fig 1). The thickness of the air film is very small at the point of contact and gradually increases from the center outwards. The fringes produced are concentric circles. With monochromatic light, bright and dark circular fringes are produced in the air film. When viewed with the white light, the fringes are coloured.

A horizontal beam of light falls on the glass plate B at an angle of 45^0. The plate B reflects a part of incident light towards the air film enclosed by the lens L and plate G. The reflected beam (see fig 1) from the air film is viewed with a microscope. Interference takes place and dark and bright circular fringes are produced. This is due to the interference between the light reflected at the lower surface of the lens and the upper surface of the plate G.

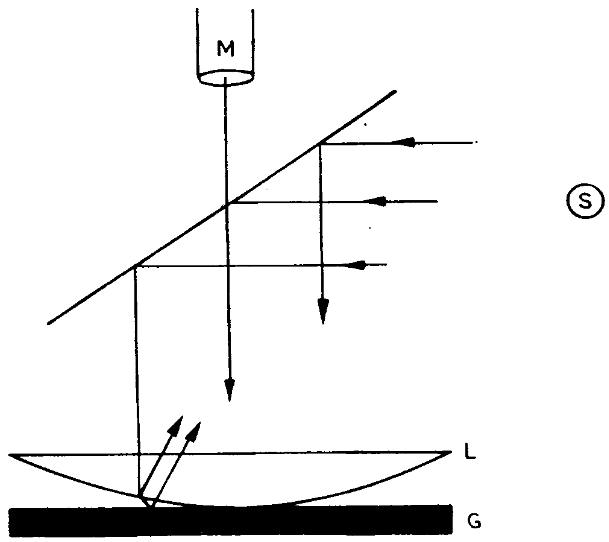


Fig 1

For the normal incidence the optical path difference between the two waves is nearly $2\mu t$, where μ is the refractive index of the film and t is the thickness of the air film. Here an extra phase difference π occurs for the ray which got reflected from upper surface of the plate G because the incident beam in this reflection goes from a rarer medium to a denser medium. Thus the conditions for constructive and destructive interference are (using $\mu = 1$ for air)

$2t = m\lambda$ for minima; $m = 0,1,2,3$…………….. ------------ **(1)**

and $2t = \left(m + \frac{1}{2}\right)\lambda$ for maxima; $m = 0,1,2,3$…………… -------------**(2)**

Then the air film enclosed between the spherical surface of R and a plane surface glass plate, gives circular rings such that (see fig 2)

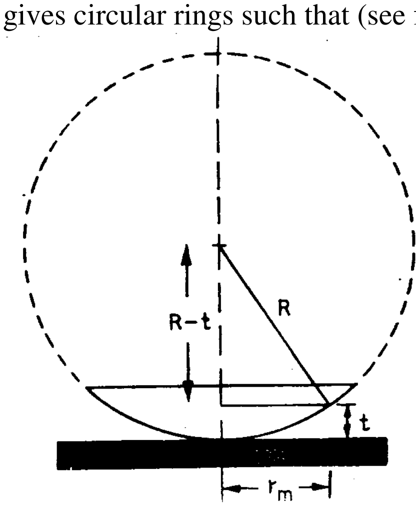


Fig. 2

$$r_m^2 = (2R-t)t$$

where r_m is the radius of the m^{th} order dark ring .(Note: The dark ring is the m^{th} dark ring excluding the central dark spot).

Now R is the order of 100 cm and t is at most 1 cm. Therefore R>>t. Hence

$$(R-t)^2 + r_m^2 = R^2 \Rightarrow r_m^2 = (2R-t)t$$

(neglecting the t^2 term), giving

$$2t \approx \frac{r_m^2}{R}$$

Putting the value of "2 t" in eq(1) gives

$$m\lambda \approx \frac{r_m^2}{R} \quad \Rightarrow r_m^2 \approx m\lambda R \ , \quad m = 0,1,2,3\ldots\ldots \quad \textbf{----------------(3)}$$

and eq (2) gives (for the radius r_m of m^{th} order bright ring)

$$\frac{r_m^2}{R} = (m+\frac{1}{2})\lambda \ \Rightarrow r_m^2 = \left(m+\frac{1}{2}\right)\lambda R \qquad \textbf{----------------------(4)}$$

Hence for dark rings

$$r_m = \sqrt{m\lambda R} \qquad \textbf{--------------------------(5)}$$

while for bright rings

$$r_m = \sqrt{\left(m+\frac{1}{2}\right)\lambda R} \ ; \qquad m = 0,1,2,3\ldots\ldots \quad \textbf{------------------------(6)}$$

With the help of a traveling microscope we can measure the diameter of the m^{th} ring order dark ring = D_m . Then $r_m = \frac{D_m}{2}$ and hence,

$$D_m^2 = 4m\lambda R \qquad \textbf{-----------------------(7)}$$

So if we know the wavelength λ, we can calculate R(radius of curvature of the lens).

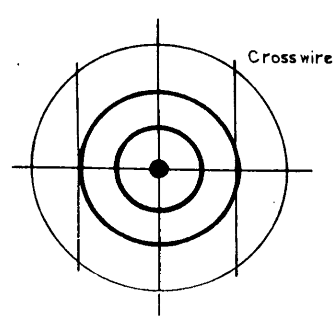
II. Setup and Procedure:

1. Clean the plate G and lens L thoroughly and put the lens over the plate with the curved surface below B making angle with G(see fig 1).

2. Switch in the monochromatic light source. This sends a parallel beam of light. This beam of light gets reflected by plate B falls on lens L.

3. Look down vertically from above the lens and see whether the center is well illuminated. On looking through the microscope, a spot with rings around it can be seen on properly focusing the microscope.

4. Once good rings are in focus, rotate the eyepiece such that out of the two perpendicular cross wires, one has its length parallel to the direction of travel of the microscope. Let this cross wire also passes through the center of the ring system.



5. Now move the microscope to focus on a ring (say, the 20th order dark ring). On one side of the center. Set the crosswire tangential to one ring as shown in fig 3. Note down the microscope reading . **fig 3 →**
   (Make sure that you correctly read the least count of the vernier in mm units)

6. Move the microscope to make the crosswire tangential to the next ring nearer to the center and note the reading. Continue with this purpose till you pass through the center. Take readings for an equal number of rings on the both sides of the center.

Precautions:
Notice that as you go away from the central dark spot the fringe width decreases. In order to minimize the errors in measurement of the diameter of the rings the following precautions should be taken:

i) *The microscope should be parallel to the edge of the glass plate.*

ii) *If you place the cross wire tangential to the outer side of a perpendicular ring on one side of the central spot then the cross wire should be placed tangential to the inner side of the same ring on the other side of the central spot.(See fig 3)*

iii) *The traveling microscope should move only in one direction.*

III. Exercises and Viva Questions:

1. What is the medium that causes the interference in this experiment? Why are the interference effects due to the glass plate and the lens ignored?

2. Explain why the interference rings are circular in shape.

3. Why do the rings get closer as the order of the rings increases?

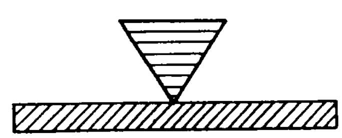
4. Show that the difference in radius between adjacent bright rings is given by

$$\Delta r = r_{m+n} - r_m \approx \frac{1}{2}\sqrt{\frac{\lambda R}{m}} \quad \text{for m >>1.}$$

5. Show that the area between adjacent rings is independent of m and is given by A= π λ R, for m >>1.

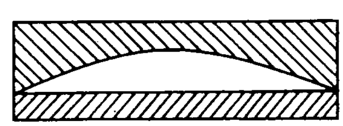
6. Why is the central spot dark? What would be the reason for not obtaining a dark central spot in the experiment?

7. What would be the shape of the rings if a wedge shaped prison went kept inverted on the glass plate?



8. What will be the effect of using a plano-convex lens in the experiment?

   Derive an expression for the radius of bright and dark rings.



9. What would be effect of using white light instead of monochromatic light?

10. Why is it necessary to use a lens of large value of R in this experiment?

Reference:

1. "Physics" ,M.Alonso and E.J.Finn, Addison-Wiley, 1992

2. "Fundamentals of Physics", D.Halliday , R.Resnick and J.Walker, 6th edition ,John-Wiley & sons , New York 2001.

Observations and results

1. Least count of vernier of traveling microscope = ____________________mm

2. Wave length of light = ________________________ m

Table 1: Measurement of diameter of the ring

S.No	Order of ring(m)	Microscope reading						Diameter	
		Left side			Right side				
		MS	VS	Net(cm)	MS	VS	Net(cm)	D(cm)	$D^2(cm^2)$
1	20								
2	18								
3	16								
4	14								
5	12								
6	10								
7	8								
8	6								
9	4								
10	2								

Calculations:

Plot the graph of D^2 vs. m and draw the straight line of best fit.

Give the calculation of the best fit analysis below. Attach extra sheets if necessary.

From the slope of the graph, calculate the radius of curvature R of the plano convex lens as

$$R = (slope) \times \frac{1}{4\lambda} = \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \text{ cm.}$$

Results: ……………………….

(One graph paper required).

Experiment 22

Diffraction at a single and double slit

Apparatus:

Optical bench, He-Ne Laser, screen with slits, photo cell, micro meter.

Purpose of the experiment:

To measure the intensity distribution due to single and double slits and to measure the slit width (d) and slit separation (a).

Basic Methodology:

Light from a He-Ne Laser source is diffracted by single and double slits. The resulting intensity variation is measured by a photo cell whose output is read off as a current measurement.

I. Introduction:

I.1 Single slit diffraction

We will study the Fraunhofer diffraction pattern produced by a slit of width 'a'. A plane wave is assumed to fall normally on the slit and we wish to calculate the intensity distribution produced on the screen. We assumed that the slit consists of a large number of equally spaced point sources and that each point on the slit is a source of Huygen's secondary wavelets which interfere with the wane lets emanating from other secondary points. Let the point sources be at A_1, A_2, A_3…..and let the distance between the consecutive points be Δ.(see fig 1). Thus, if the number of point sources be n, then

$$a = (n-1)\Delta. \qquad \text{-------------------------------------(1).}$$

We now calculate the resultant field produced by these n sources at point P on the screen. Since the slit actually consists of a continuous distribution of sources , we will in the final expression, let n go to infinity and Δ go to zero such that $n\Delta$ tends to a.

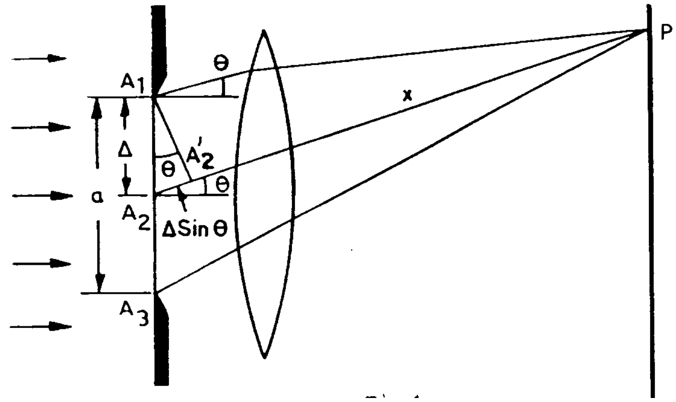


Fig 1.

Now at point P the amplitudes the disturbances reaching from A_1, A_2, ….. will be very nearly the same because the point at a distance which is very large in comparison to a. However, because of even slightly different path lengths ti the pint P, the field produced by A_1 will differ in phase from the field produced by A_2.

For an incident plane waves, the points A_1, A_2.. are in phase and, therefore, the additional path traversed by the disturbance emanating from the point $A_2\,A_2^{/}$. This follows from the fact the optical paths A_1B_1P and $A_2^{/}\,B_2P$ are the same. If the diffracted rays make an angle θ with the normal to the slit the path difference would be

$$A_2\,A_2^{/} = \Delta \sin\theta \qquad \text{--------------------------------}(2)$$

The corresponding phase difference, ϕ, would be given by

$$\phi = \frac{2\pi}{\lambda}\Delta\sin\theta \qquad \text{----------------------------------- } (3)$$

Thus, if the field at the point P due to the disturbance emanating from the point A_1 is $a\cos(\omega t)$ then the field due to the disturbance emending from A_2 would be emanating $a\cos(\omega t - \phi)$. Now the difference in phases of the disturbance reaching from A_2 and A_3 will also be ϕ and thus the resultant field at the point P would be given by

$$E = E_0\left[\cos(\omega t) + \cos(\omega t - \phi) + \dots\dots\dots + \cos(\omega t - (n-1)\phi)\right] \quad \text{----------- } (4)$$

Because

$$\cos(\omega t) + \cos(\omega t - \phi) + \dots\dots\dots + \cos(\omega t - (n-1)\phi)$$

$$= \frac{\sin\frac{n\phi}{2}}{\sin\frac{\phi}{2}} \quad \cos\left[\omega t - \frac{1}{2}(n-1)\phi\right] \qquad \text{----------------------- } (5)$$

Thus, $$E = E_\theta \cos\left[\omega t - \frac{1}{2}(n-1)\phi\right] \qquad \text{-------------------------- } (6)$$

Where the amplitude E_0 of the resultant field would be given by

$$E_\theta = \frac{E_0 \sin\left(\frac{n\phi}{2}\right)}{\sin\frac{\phi}{2}} \qquad \text{--------------------------------------}$$

(7)

In the limit of n → ∞ and Δ → 0 in such a way that n Δ → a, we have

$$\frac{n\phi}{2} = \frac{n}{2}\frac{2\pi}{\lambda}\Delta\sin\theta \rightarrow \frac{\pi}{\lambda}a\sin\theta$$

Further $\phi = \frac{2\pi}{\lambda}\Delta\sin\theta = \frac{2\pi}{\lambda}\frac{a}{n}\sin\theta$ would tend to zero and we may therefore,

$$\text{write } E_\theta = \frac{E_0 \sin\frac{n\phi}{2}}{\frac{\phi}{2}} = n E_0 \frac{\sin\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\frac{\pi}{\lambda} a \sin\theta} = A \frac{\sin\beta}{\beta} \qquad \text{-------------------------- } \mathbf{(8)}$$

where,

$$A = n E_0 \quad \text{and} \quad \beta = \frac{\pi a \sin\theta}{\lambda} \qquad \text{----------------------------- } \mathbf{(9)}$$

$$\text{thus,} \qquad E = A \frac{\sin\beta}{\beta} \cos(\omega t - \beta) \qquad \text{----------------------------}\mathbf{(10).}$$

The corresponding intensity distribution is given by

$$I = I_0 \frac{\sin^2\beta}{\beta^2} \qquad \text{--------------------------------- } \mathbf{(11)}$$

where I_0 represent the intensity at $\theta = 0$.

I.2. Positions of the maxima and minima:

The variation of the intensity with β is shown in fig 2a. From eq(11) it is obvious that the intensity is zero when

$$B = m\,\pi, \quad m \neq 0 \qquad \text{--------------------------------- } \mathbf{(12)}$$

or

$$a \sin\theta = m\,\lambda\,; \;\; m = \pm 1, \; \pm 2, \; \pm 3 \text{ (minima)}$$

In order to determine the position of the minima, we differentiate eq(11) wrt. β and set it equal to zero.

This gives

$$\text{Tan } \beta = \beta \quad \text{(maxima)} \qquad \text{---------------------------- } \mathbf{(13)}$$

The root $\beta = 0$ corresponds to the central maximum. The other roots can be found by determining the points of intersections of the curves $y = \beta$ and $y = \tan\beta$ (fig 2 b,c). The intersections occur at $\beta = 1.43\,\pi$, $\beta = 2.46\,\pi$ etc. and are known as the first , second maximum etc. Since $\left[\frac{\sin(1.43\pi)}{1.43\pi}\right]^2$ is about 0.0496, the intensity of the first maximum is about 4.96% of the central maxima. Similarly the intensities of the second and third maximum are about 1.88% and 0.83% of the central maximum respectively.

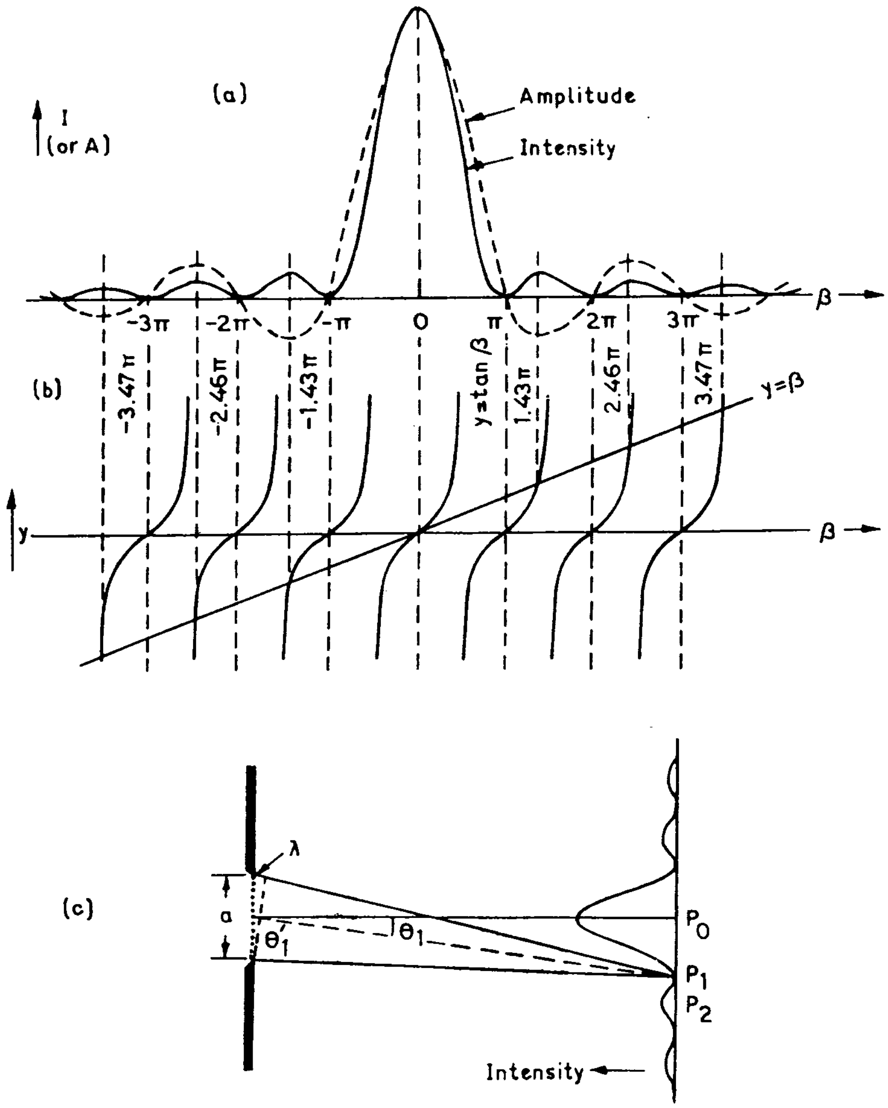


Fig 2

I.3. Double slit diffraction pattern:

In this section we will study the Fraunhofer diffraction pattern produced by two parallel slits (each of width a) separates by a distance d. We would find that the resultant intensity distribution is a product of single slit diffraction pattern and the interference pattern produced by two point sources separated by a distance d.

In order to calculate the diffraction we use a method similar to that used for the case of a single slit and assume that the slits consists of a large number of equally spaced point sources and that each point on the slit is a source of Huygen's secondary wavelets. Let the point sources be at A_1, A_2, A_3,….(in the first slit) and at b_1, b_2, b_3…(in the second slit)(see fig3). As before, we assume that the distances between two consecutive points in either of the slit is Δ. Then the path difference between the disturbances reaching the point P from two consecutive point in a slit will be $\Delta \sin \theta$. The field produced by the first slit at the point P will, there fore, be given by (see eq

10)

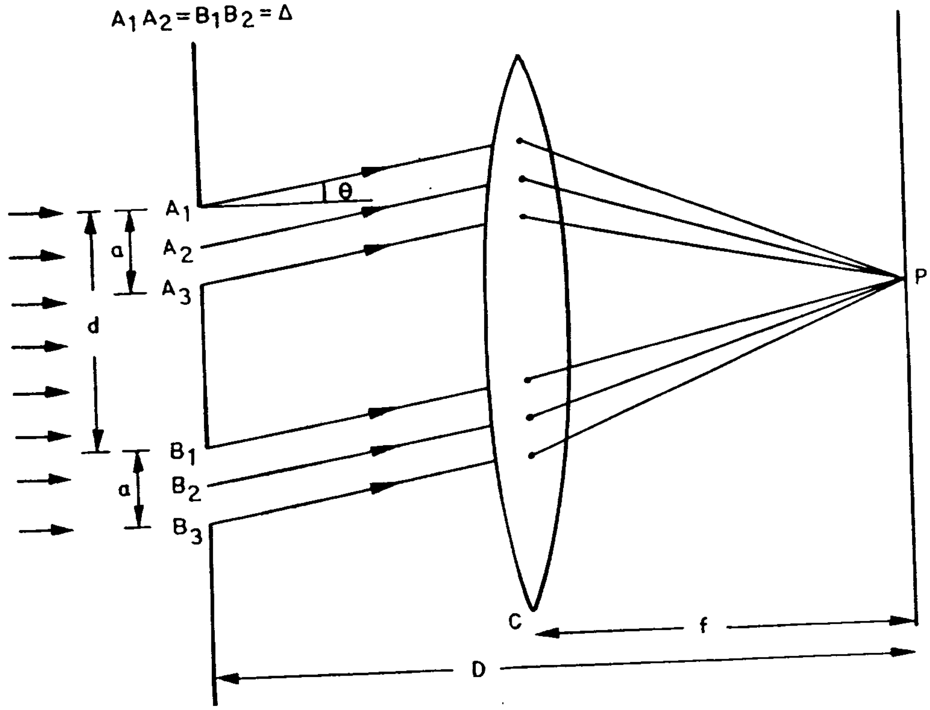


Fig 3

$$E_1 = A\frac{\sin\beta}{\beta}\cos(\omega t-\beta) \qquad \textbf{------------------------------------ (14)}$$

Similarly, the secondary slit will produce a field

$$E_2 = A\frac{\sin\beta}{\beta}\cos(\omega t-\beta-\Phi_1) \qquad \textbf{------------------------------ (15)}$$

at the point P, where $\Phi_1 = \frac{2\pi}{\lambda} d\sin\theta$ represents the phase difference between the disturbances from two corresponding points on the slits; by corresponding points we imply pair of points like (A_1 ,B_1), (A_2 ,B_2)……., which are separated by a distance d. Hence the resultant field will be

$$E = E_1 + E_2 = A\frac{\sin\beta}{\beta}\left[\cos(\omega t-\beta)+\cos(\omega t-\beta-\Phi_1)\right]$$

which represents the interference of two waves each of amplitude $A\frac{\sin\beta}{\beta}$ and differing in phase by Φ_1. Above equation can be written as

$$E = A\frac{\sin\beta}{\beta}\cos\gamma\cos(\omega t-\beta-\frac{\Phi_1}{2})$$

where $\gamma = \frac{\Phi_1}{2} = \frac{\pi}{\lambda} d\sin\theta$.

The intensity distribution will be of the form

$$I = 4I_0\frac{\sin^2\beta}{\beta^2}\cos^2\gamma \qquad \textbf{----------------------------------- (16)}$$

where $I_0 \frac{\sin^2\beta}{\beta^2}$ represents the intensity distribution produced by one of the slits. As a can be seen, the intensity distribution is a product of two terms, the first term $\left(\frac{\sin^2\beta}{\beta^2}\right)$ represents the diffraction produced by a single slit of width a and the second term ($\cos^2\gamma$) represents the interference pattern producedby two point sources separated by a distance d(see fig4)

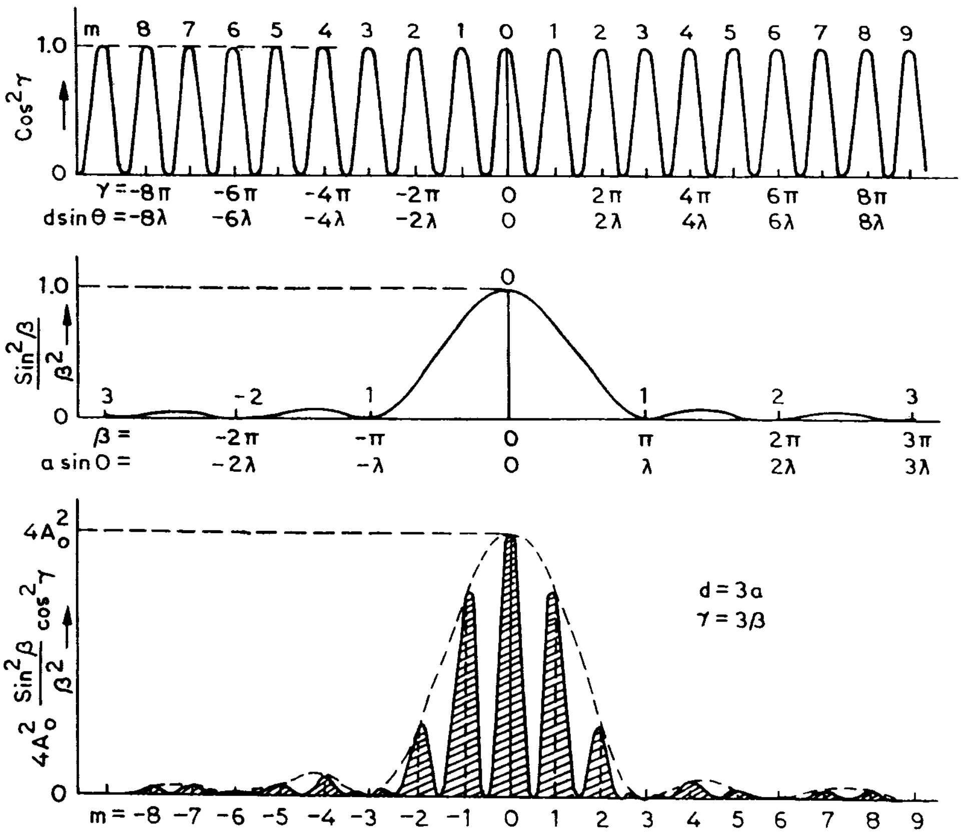


Fig 4

I.4. Positions of Maxima & Minima:

Equation (16) tells us that the intensity is zero wherever $\beta = \pi, 2\pi, 3\pi\ldots$

or when $\gamma = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}.....$

The corresponding angles of diffraction will be given by

$$a \sin\theta = m\lambda \;;\; (m = 1,2,3..)$$

and

$$d\sin\theta = \left(n + \frac{1}{2}\right)\lambda \;; \qquad (n = 0, 1, 2, 3\ldots) \text{ ----------------- } \mathbf{(17)}$$

Interference maxima occur when

$$\gamma = 0, \pi, 2\pi, 3\pi.....$$

or when

$$d \sin\theta = 0, \lambda, 2\lambda, 3\lambda.....$$

II. Setup and Procedure:

1. Switch on the laser source about 15 minutes before the experiment is due to start. This ensures that the intensity of light from the laser source is constant.

2. Allow the laser beam to fall on a slit formed in the screen provided.

3. The intensity distribution in the diffraction pattern is measured with the help of a photo cell. The photo cell is secured to a mount and is kept as far behind the slit as possible. A screen with a slit (0.3mm wide) is fitted in front of the photocell. The photo current is measured with a multimeter(μ A) range and is approximately proportional to intensity of the incident light.

4. Repeat the same procedure for double slit and record the diffraction pattern on both the sides of central maximum. The interval between two consecutive minima positions of the photocell should be small enough, so that adjacent maxima/minima of the intensity distribution are missed.

Precautions:

1. The laser beam should not penetrate into e yes as this may damages the eyes permanently.

2. The photo cell should be as away from the slit as possible.

3. The laser should be operated at a constant voltage 220V obtained from a stabilizer. This avoids the flickering of the laser beam.

III. Exercises and Viva Questions:

1. What are the characteristics of light produced by a laser? Can this experiment conducted by using any other source?

2. Verify eq(4).

3. For a traveling wave, derive the relation between path difference and phase differences.

4. What is the effect on the intensity distribution if the slit with 'a' is changed ? If the slit separation'd' is changed?

5. What would be the result if the experiment were to be carried out with white light?

6. What is the intensity distribution for a double slit ignoring diffraction effects?

7. Count the number of interference fringes observed with in the envelope of central diffraction maximum. Give an example based on the experiment for the number of fringes seen.

8. What is the effect on the intensity pattern if the distance D between slit and photocell is changed?

9. How much D change for a bright fringe at the photocell should be replaced by dark fringe?

10. What will be the intensity pattern for a 3-slit interference?

Reference:

1. "Fundamentals of Optics", F.A.jenkins and H,E.white, McGraw-Hill International(4th edition),1976.

2. "Optics", A.Ghatak, Tata McGraw-Hill(2nd edition), 1992.

3. **"**Fundamentals of Physics", D.Halliday, R.Resnick and J.Walker, 6th edition John-Wiley & sons , New York 2001

Appendix: Lasers

Introduction:

The light emitted from a conventional light source is(like sodium lamp) is said to be incoherent because the radiation emitted from different atoms do not, in general, bear any definite phase relationship with each other. On the other hand, the light emitted from a laser has a very high degree of coherence and is almost perfectly collimated.

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The basic principle involved in lasing action is the phenomenon of stimulated emission, which was predicted by Einestein in 1917. Einestein argued that when an atom is in the excited state, it can make a transition to a lower energy state through the emission of electromagnetic radiation; however, in contrast to the absorption process, the emission ca be occur in two different ways:

i). The first is referred to as *spontaneous emission* in which an atom in the excited state emits radiation even in the absence of any incident. It is thus not stimulated by any incident signal but occurs spontaneously.

ii) The second is referred to as *stimulated emission* in which an incident signal of appropriate frequency triggers an atom in an excited state to emit radiation.

Using the phenomenon of stimulated emission, C.H. Townes and A.H. Schawlow, in 1958, worked out the principle of the laser.

Stimulated Emission:

Consider a gas enclosed in a vessel containing free atoms having a number of energy levels, at least one of which is *metastable*. By shining white light into this gas many can be excited, through resonance, from the ground state to excited states. As the electron drop back, many of them will become trapped in the metastable states. If the pumping light is intense enough we may obtain a population inversion, i.e. more electrons in the metastable state than in the ground state.

When an electron in one of these metastable states spontaneously jumps to the ground state, it emits a photon. As the photon passes by another nearby atom in the same metastable state, it stimulates that atom to radiate a photon of the exact same frequency, direction, and polarization as the primary photon and exactly the same phase. Both of these photons upon passing close to other atoms in their metastable states, stimulates them to emit in the same direction with the same phase. However, transitions from the ground state to the excited state can also be stimulated thereby absorbing the primary photons. An excess of stimulated emission gives population inversion. Thus, if the conditions in the gas are right, a chain reaction can be developed, resulting in high intensity coherent radiation.

Laser Design:

In order to produce a laser, one must collimate the stimulated emission, and this is done by properly designing a cavity in which the waves can be used over and over again. For this, a cavity is attached with two end mirrors with high reflecting power and into this cavity is introduced an appropriate solid, liquid, or gas having metastable states in the atoms or molecule. The electrons in these atoms are excoted and produce a population inversion of atoms in a metastable state, which spontaneously radiate. Photons moving at an appreciate angle to the walls of the cavity will escape and be lost. Those photons emitted parallel to the axis will reflect back and forth from end to end. Their chance of stimulating emission will now depend on the high reflectance at the end mirror and a high population density of metastable atoms within the cavity. If both these conditions are satisfied the build-up of photons surging back and forth through the cavity can be self sustaining and the system will oscillate or lase, spontaneously.

Helium – Neon Gas Laser:
The He – Ne laser was first fabricated by A I Jaran and Harriot in 1961 at Bell Telephone laboratories in USA. This consists of a mixture of helium and neon gases in a ratio of about 10 : 1, placed inside a long narrow discharge tube.(see fig.5). The pressure inside the tube is 1 mm of Hg. The gas system is enclosed between a pair of plane mirrors. One of the mirror is of high reflectivity while the other is partially transparent so that the energy may be out of the system.

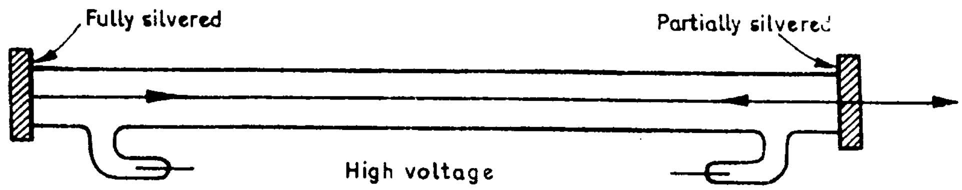


Fig 5

All the lower energy levels of He and Ne are shown in an energy level diagram in fig 6. The normal state of helium is $^1S_0$ level arising from two valence electrons in 1s orbits. The excitation of either one of these electrons to the 2s orbit finds the atom in a $^1S_0$ or $^3S_1$ state, both quite metastable, since transitions to the normal state are forbidden by selection rules.

Neon, with Z = 10, has 10 electrons in the normal state and is represented by the configuration, $1s^2$, $2s^2$, $2p^6$. when one of the six 2p electrons are excited to the 3s, 3p, 4s, 4p, 4d, 4f, 5s, etc., orbit, triplet and singlet energy levels arise. A sub shell like $2p^5$, containing one $2p^5$ electron. The number and designations of the levels produced are therefore the same as for two electrons, all triplets and singlets.

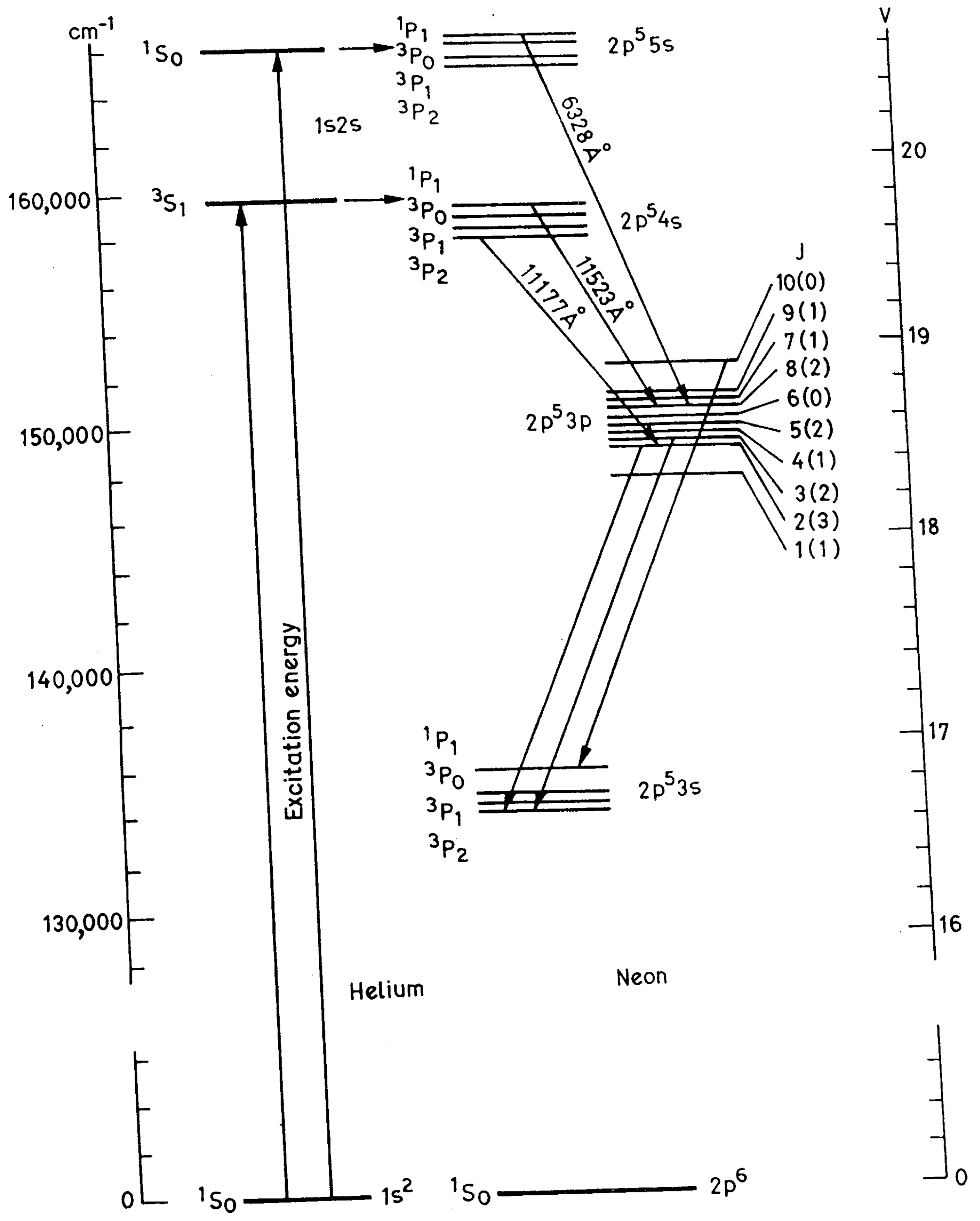
As free electrons collide with helium atoms during the electric discharge, one of the two bound electrons may be excited to 2s orbits, i.e., to the $^3S_1$ or $^1S_0$ states. Since downward transitions are forbidden by radiation selection rules, these are meta stable states and the number of excited atoms increases. We therefore have optical pumping, out of the ground stae $^1S_0$ and in to the metastable states $^3S_1$ and $^1S_0$.

When one metastable helium atom collides with a non atom in its ground state, there is a high probability that the high excitation energy will be transferred to the neon, raising it to one of the $^1P_1$ or $^3P_0$, $^3P_1$, or $^3P_2$ levels of $2p^55s$. The small excess energy is converted in to kinetic energy of the colliding atoms.

In this process each helium atom returns to the ground state as each colliding neon atom is excited to the upper level of corresponding energy. The probability of a neon atom being raised to the $2p^53s$ or $2p^53p$ levels by collision is extremely small because of the large energy mismatch. The collision transfer therefore selectively increases the population of the upper levels of neon.

Since selection rules permit transitions from these levels downward to the 10 levels of $2p^53p$ and these in turn to the 4 levels of $2p^53s$, stimulated emission can speed up the process of lasing . Lasing requires only that the 4s and 5s levels of the neon be more densely populated than the 3p levels. Since the 3p levels of neon are more sparsely populated, lasing can be initiated with out pumping a major of the atoms out of the ground state.

Light waves emitted with in the laser at wavelengths such as 6328,11,177 and 11,523 A^0 will occasionally be omitted parallel to the tube axis .Bouncing back and forth between the end mirrors, these waves will simulate emission of the same frequency from other excited neon atoms , and the initial wave with the stimulated wave will travel parallel to the axis. Most of the amplified radiation emerging from the ends of the He – Ne gas laser are in the near infrared region of the spectrum , between 10,000 and 35,000 A^0, the most intense amplified wavelength in the visible spectrum being the red line at 6328 A^0.



Experiment 21
Diffraction at a single and Double slit.

Observations and Results

Wavelength of He-Ne laser = 623.8 nm.

Distance D between slit and photocell = ________________________ cm.

Least count of screw gauge = ________________________________ cm.

Table 1 : Single slit diffraction

S.No	Position of photocell (mm) Main Scale +	Vernier =	Net	Current μA
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				

Table 2: Double Slit diffraction

S.No	Position of photocell (mm) Main Scale +	Vernier =	Net	Current μA
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				
37				
38				
39				
40				

Calculations & Results:

1. Determination of width od single slit ‘a’

   Plot a graph of current Vs position of the photocell. Using data from Table1. Measure the distance x from center of diffraction pattern to the first minimum of the graph paper. Calculate the slit width ‘a’ using (m=1 in eq. 12).

$$a \sin\theta = a\,\frac{X}{\sqrt{X^2 + D^2}} = \lambda$$

2. Determination of a & d for double slit

   Plot a graph of current Vs position of the photocell using data of Table 2. Measuer the distance X of the first minimum of the diffraction envelope from the center of the diffraction pattern (see Fig 4). Measure also the distance y between two consecutive minima of the interface pattern with the diffraction envelope (see Fig 4). Calculate a and d using the following relations.

$$\frac{aX}{\sqrt{X^2 + D^2}} = \lambda \quad (m=1\ in\ \ eq.12)$$

$$\frac{d\left(\frac{y}{2}\right)}{\sqrt{D^2 + \frac{y^2}{4}}} = \frac{\lambda}{2} \qquad (\ n = 1\ \ in\ eq.\ 17\ )$$

Results

1. The width of the single slit = ______________________________ mm.

2. For the double slit a = ___________________________________ mm.

   b = ___________________________________ mm.

(Two graph papers required).

Experiment 23

Diffraction Grating

Apparatus

Spectrometer, grating, sodium lamp, mercury lamp, power supply for spetral lamps, magnifying glass.

Objective of the experiment:

a. To calibrate the grating spectrometer using the known source (Hg source) of light and to calculate the grating constant.
b. Using the same grating, to calculate the wavelength of sodium –D lines

Basic methodology:

Light from a mercury lamp source is made to fall normally on a grating mounted on a spectrometer. The diffraction angle of the diffracted light is measured for each spectral line of the Hg-source. Likewise for sodium source, the diffraction angle and angular separation $\Delta\theta$ of the sodium doublet is measured.

I. Introduction

I.1 Diffraction grating

A diffraction grating is a very powerful and precise instrument for the study of spectra and is widely used in a large number of fields from Astronomy to Engineering, wherever there is a need for detection of the presence of atomic elements.

A diffraction grating can be simply thought of as a set of identical and equally spaced slits separated by opaque strips. In reality gratings are made by ruling fine grooves by a diamond point either on a plane glass surface to produce a transmission grating or on a metal mirror to produce a reflection grating. In a transmission grating the grooves scatter light and so are opaque while the unruled surfaces transmit and act like slits. Typically a high quality grating (used for studying spectra in the visible range) has about 15000 grooves per inch, which gives a slit spacing of the order of a micron.

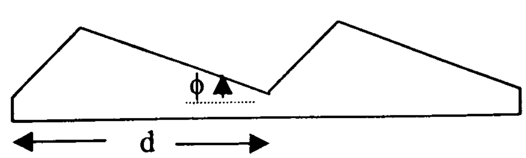


Fig. 1

The chief requirement of a good grating is that the lines be equally spaced over the width of the ruled surface, which can vary from 1-25 cm. After each groove has been ruled, the machine lifts the diamond point and moves the grating forward by a small rotation of a screw. For rulings of equal spacing the screw must have a constant pitch. Replication gratings are also used, in which a cast of the ruled surface is taken with some transparent material. Replication grating give satisfactory performance where very high resolving power is not required. A typical groove profile is the triangular blazed profile shown in Fig. 1. The angle φ is called the blaze angle.

I.2 Basic Theory

When a wave front is incident on a grating surface, light is transmitted through the slits and obstructed by the opaque portions. The secondary waves from the positions of the slit interface with one another, similar to the interference of waves in Young's experiment. If the spacing between the lines is of the order of the wavelength of light then an appreciable deviation of the light is produced.

Consider the diffraction pattern produced by N parallel slits, each of width b; the distance between two consecutive slits is assumed to be d (See fig. 2).

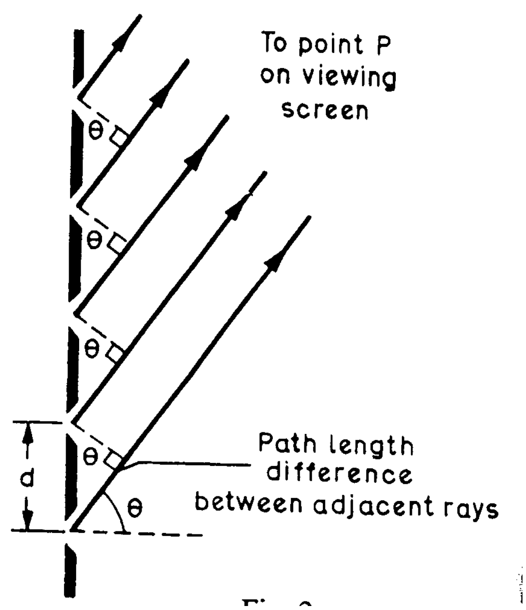


Fig. 2

The field at any arbitrary point P will essentially be a sum of N turns (recall the derivation for the double slit),

$$E = A\frac{\sin\beta}{\beta}Cos(\omega t-\beta)+A\frac{\sin\beta}{\beta}\cos(\omega t-\beta-\phi_1)+.......+A\frac{\sin\beta}{\beta}\cos(\omega t-\beta-(N-1)\phi_1) \quad \text{--------------------(1)}$$

$$E = A\frac{\sin\beta}{\beta}\frac{\sin N\gamma}{\sin\gamma}\cos[\omega t-\beta-\tfrac{1}{2}(N-1)\phi_1], \quad \text{------------------(2)}$$

where $\beta = \dfrac{\pi b\sin\theta}{\lambda}$ and $\gamma = \dfrac{\phi_1}{2} = \dfrac{\pi d\sin\theta}{\lambda}$

and φ_1 is the phase difference between the light rays emanating from successive slits. The corresponding intensity distribution will be

$$I = I_0\frac{\sin^2\beta}{\beta^2}\frac{\sin^2 N\gamma}{\sin^2\gamma} \quad \text{------------------(3)}$$

As can be seen, the intensity distribution is a product of two terms, the first term

$\left[\frac{\sin^2\beta}{\beta^2}\right]$ represents the diffraction pattern produced by a single slit and the second term represents the interference pattern produced by N equally spaced slits. For N=1 eqn. (3) reduces to the single slit diffraction pattern and for N=2, to the double slit diffraction pattern.

I.3 Principal Maxima

When the value of N is very large, one obtains intense maxima at $\gamma = m\pi$ i.e. when

$$d\sin\theta = m\lambda \text{ , } m=0,\ 1,\ 2,\ \ldots\ldots\ldots \qquad \text{(Maxima)} \qquad \ldots\ldots\ldots \ (4)$$

Thus it can be easily seen by noting that

$$\lim_{\gamma\to m\pi}\frac{\sin N\gamma}{\sin\gamma} = \lim_{\gamma\to m\pi}\frac{N\cos N\gamma}{\cos\gamma} = \pm N$$

Thus, the resultant amplitude will be

$$E(\theta) = NA\frac{\sin\beta}{\beta}$$

and the corresponding intensity distributions are given by

$$I = N^2 I_0 \frac{\sin^2\beta}{\beta^2}, \text{ where } \beta = \frac{\pi b\sin\theta}{\lambda} = \frac{\pi bm}{d}$$

Such maxima are known as principal maxima. Physically, at these maxima the fields produced by each of the slits are in phase and therefore, thay add up and the resultant fields is N times the field produced by each of the slits.

I.4 Minima and secondary maxima

To find the minima of the function $\sin^2 N\gamma \big/ \sin^2\gamma$ we note that the numerator becomes zero at $N\gamma = 0, \pi, 2\pi$ or in general, pπ where p is an integer. In the special case when p=0, N, 2N …., γ will be 0, π, 2π; …. For these values the denominator will also vanish, and we have the principal maxima descrined above. The other values of p give zero intensity since for these the denominator does not vanish at the same time. Hence, the condition for minima is $\gamma = p\pi/N$, excluding those values of p for which p=mN, m being the order. These values of γ corresponds to

$$d\sin\theta = \frac{\lambda}{N}, \frac{2\lambda}{N}, \frac{3\lambda}{N}, \ldots\ldots, \frac{(N-1)\lambda}{N}, \frac{(N+1)\lambda}{N} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Omitting the values 0, $\frac{N\lambda}{N}, \frac{2N\lambda}{N}$,...... for which $d\sin\theta = m\lambda$ and which corresponds to principal maxima. Thus, between two principal maxima we have (N-1) minima. Between two such consecutive minima the intensity has to have a maxima; these maxima are known as secondary maxima. These are of much smaller intensity than principal maxima. The principal maxima are called spectrum lines.

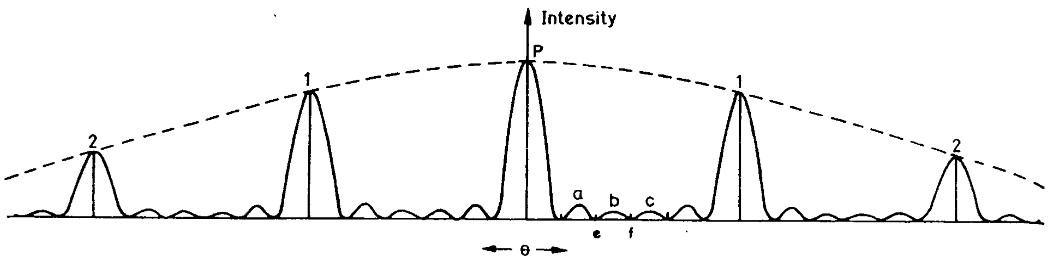


Fig. 3

The intensity distribution of the screen is shown in Fig. 3. P corresponds to the position of the central maxima and 1, 2 etc on the two sides of P represents the 1st, 2nd etc principal maxima. a, b, c etc are secondary maxima and e, f, etc are the secondary minima. The intensity as well as the angular spacing of the secondary maxima and minima are so small in comparison to the principal maxima that they can not be observed. This results in uniform darkness between any two principal maxima.

I.5 Dodium D lines

The sodium doublet is responsible for the bright yellow light from a sodium lamp. The doublet arises from the 3p→3s transition, in the sodium atom. The 3p level splits into two closely spaced level with an energy spacing of 0.0021 eV. The splitting occurs due to the spin orbit effect. This can be crudely thought of as arising due to the internal magnetic field produced by the electron's circulation around the nucleus and the splitting takes place anologus to the Zeeman effect. Fig. 4 shows the 3p and 3s levels their splitting and the radiative transition that produces the sodium doublets or D lines.

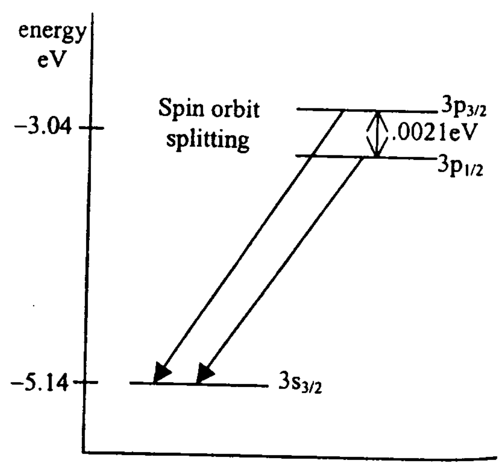


Fig. 4

II. Set-up and procedure:

PART A: Calibration of diffraction grating:

1. Adjust telescope for parallel rays i.e. focus telescope on the object at infinity. Here we

can adjust telescope on an object which is at very large distance. Level the spectrometer and prism table on which grating is mounted using a spirit level. Fig. 5 schematically shows the arrangement of the grating and the spectrometer.

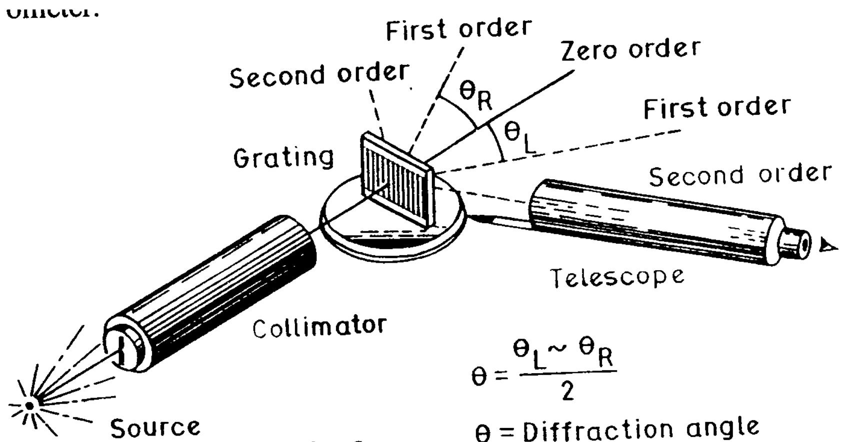


Fig. 5

2. Switch on the power supply for spectral lamp.
3. Place the grating on the prism table such that the surface of the grating is approximately perpendicular to the collimator of the spectrometer (i.e. perpendicular to the incident slit falling on the grating). Fix the prism table in this position. With the Hg source observe first order spectrum on left hand side and right hand side. Measure the angle of diffraction of each line by rotating telescope so that cross-wire coincides with particular spectral line. Note down each measurement on the observation table I. The diffraction angle is equal to difference between LHS and RHS observation divided by two for a particular spectral line. (See Fig. 5).

   The wavelength of the main spectral lines of Hg in the visible region are given in Table I.

   PART B: To measure the wavelength of second sodium light (D2)

4. Repeat step 2 and 3 with sodium source. In first order spectrum of sodium measure the angular position θ_L of yellow 1 (D1) on the left side. Use the micrometer screw to turn the telescope to align the crosswire at the second yellow line (D2) and read its angular position θ_L.
5. Likewise measure θ_R on the RHS for D1 and D2.

Precautions:

1. The experiment should be performed in a dark room.
2. Micrometer screw should be used for fine adjustment of the telescope. For fine adjustment the telescope should be first licked by means of the head screw.
3. The directions of rotation of the micrometer screw should be maintained otherwise the play in the micrometer spindle might lead to errors.
4. The spectral lams (mercury source) attain their full illuminating power after being warmed up for about 5 minutes, observation should be taken after 5 minutes.
5. One of the essential precautions for the success of this experient is to set the grating normal to the incident rays (see below). Small variation on the angle of incident causes

correspondingly large error in the angle of diffraction. If the exact normally is not observed, one find that the angle of diffraction measured on the left and on the right are not exactly equal. Read both the verniers to eliminate any errors due to non-coincidence of the center of the circular sale with the axis of rotation of the telescope or table.

Method to make light fall normal to the grating surface:

a) First mount grating approximately normal to the collimator. See the slit through telescope and take reading from one side of vernier window. Note down the reading.
b) Add or subtract (whichever is convenient) 90^0 from reading taken in step (a) and put telescope to this position. In this position telescope is approximately perperdicular to the collimator.
c) Now rotate prism table until the slit is visible on the cross-wire of the telescope. At this position the incident light from the collimator falls at an angle 45^0 with the plane of the grating. Note down this reading.
d) Next add or substract 45^o to step (c) reading and rotate the prism table so as to obtain this reading on the same window. In this situation, light incident in the grating surface is perpendicular.

III. Exercise and viva questions:

1. What is a diffraction grating? How are they made? Name three different types of gratings.
2. Can a gratingbe used for studying spectra in the UV or infrared region? If so, what should be its characteristic? Can a prism be so used? What are the advantages of a grating over a prism?
3. The dispersion of a grating is defined as $D=\Delta\theta/\Delta\lambda$ where $\Delta\theta$ is the angular separation of the principal maxima of two linees whose wavelengths differ by $\Delta\lambda$. Show that the dispersion of a grating is $D=m/(d\cos\theta)$ at the m-th order. Calculate D for the sodium doublet at the first order for your experiment.
4. The resolving power of a grating is defined as $R=\lambda_{avg}/\Delta\lambda$ where λ_{avg} is the mean wavelength and $\Delta\lambda$ the difference in the wavelength of two spectral lines which can just be resolved into two lines. It can be shown that R=Nm, where N is the total number of ruling on the grating and m is the order at which the two spectral ines can be resolved. Calculate the number of rulings required to resolve the sodium doublet at the first order.
5. Use Bohr model for the frequency of light emitted in atomic transitions to calculate the wavelengths foe the sodium doublet, using Fig. 4.
6. In the Hg spectrum which lines are prominent and which are weak? What could be the reason for variation in intensities of spectral ines?
7. What would be the advantages and disadvantages of looking at the second order spectra in this experiment?
8. What is the mechanism by which the emission spectrum is produced in the spectral lamps 9Na or Hg)? Look up Ref. 2 for details.
9. What will happen if the incident light does not fall normally on the grating? Show that if ϕ is the angle of incidence w.r.t. the normal to the grating, then the principal maxima occur at angles θ w.r.t. normal such that $\boldsymbol{d}(\sin\boldsymbol{\theta}+\sin\boldsymbol{\phi})=\boldsymbol{m\lambda}$.

References:

1. "Advanced Practical Physics for students", B. L. Worsnop and H.T. Flint, Metheun

London, 1942.
2. "Fundamentals of Optics", F.A. Jenkins and H.E. White, 4^{th} edition, McGraw-Hill Inc, 1981.
3. "Fundamentals of Physics", D. Halliday, R. Resnick and J.A. Walker, 6^{th} Ed. John Willey and Sons, New York, 2001.
4. "Optics", A. Ghatak, 2^{nd} Ed, Tata McGraw-Hill, New Delhi 1992.

Experiment 22

Observations and Results

Table I

S.No.	Spectral line	Wavelength in A°	Position of Telescope						$\theta = \frac{\theta_L - \theta_R}{2}$	Sinθ
			Left side θ_L (degree minutes)			Right side θ_R (degree minutes)				
			Main	Vernier	Total	Main	Vernier	Total		
1	**Volet-I**	4047								
2	Violet-II	4078								
3	Blue	4358								
4	Bluish-green	4916								
5	Green	5461								
6	Yellow I	5770								
7	Yellow II	5791								

Table II

S.No.	Spectral line	Wavelength in A°	Position of Telescope						$\theta = \frac{\theta_L - \theta_R}{2}$	Sinθ
			Left side θ_L (degree minutes)			Right side θ_R (degree minutes)				
			Main	Vernier	Total	Main	Vernier	Total		
1	**Volet-I**	5890								
2	Violet-II	5896								

1. Angular position θ of yellow line in first order = …………….
2. Angular separation Δθ between two yellow lines in first order = ………………

Calculations:

1. Using data of Table I, plot a graph between sinθ and λ , determine the grating constant d from the slope of the graph.
2. Using above graph, find out the values of λ corresponding to the values of sinθ quoted in Table 2. These are the wavelengths of spectral lines of sodium. Determine the wavelength separation Δλ.
3. Differentiate eqn. (4) for first order,

$$(\boldsymbol{d}\cos\boldsymbol{\theta})\Delta\boldsymbol{\theta} = \Delta\boldsymbol{\lambda}$$

Use above equation to calculate the wavelength separation between two yellow lines since d, θ, and Δθ are known from table 2.

Results:

1. Wavelength of the spectral lines of Hg are given in table I.
2. The grating constant d is found to be ……………….
3. The wavelengths of spectral lines of sodium are ………..
4. The wavelength separation between the sodium doublet lines (found from graph) is Δλ= ……………………………Å.
5. The wavelength separation between sodium doublet lines (calculated as in step 3 above) is Δλ= ……………………………Å.

(One graph paper required)

Experiment 24

Speed of light in glass

Apparatus

Prism, spectrometer, monochromatic light source, spirit level.

Objective

To determine the speed of propagation of light waves in glass.

Theory

Light travels with the speed $c = 2.998 \times 10^8$ m s^{-1} in vacuum. In a material medium its speed (v) is less. As a result, light waves undergo refraction at the interface of two media. In this experiment, we take the material of the medium in the form of a glass prism. A parallel stream of waves traveling from a medium 1 (here air) is incident on the interface of air and glass (of the prism), at the angle incidence θ_1. The angle of refraction is θ_2. Snell's law connects the two by the relation,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \ldots\ldots\ldots\ldots (1)$$

where n_1 and n_2 are the refractive indices of the two media 1 and 2 respectively.

Since the medium 1 here is air ($n_1 \cong 1.000$), the speed of light in the second medium is given by

$$\nu = c(\sin\theta_2 / \sin\theta_1) \qquad \ldots\ldots\ldots\ldots (2)$$

We know that for a certain direction of incidence, the ray travels parallel to the base of the prism and the angular displacement of the final ray that emerges from the second interface of the prism has the lowest possible value. For this minimum angular deviation, δ_m, and the corresponding incidence angle θ_1, the geometry of symmetric propagation inside the medium leads to the equation for ν

$$\nu = c \, \frac{\sin(\alpha/2)}{\sin(\alpha+\partial_m)/2} \qquad \ldots\ldots\ldots\ldots (3)$$

where α is the angle of the prism. Thus, from a measurement of the angle of the prism and the value of the minimum angular displacement δ_m, the speed of light in the material can be determined.

Procedure

A spectrometer is used to measure the necessary angles. The spectrometer consists of three units: (1) collimator, (2) telescope, and (3) prism table.

The prism table, its base and telescope can be independently moved around their common vertical axis. A circular angular scale enables one to read angular displacements (together with two verniers located diametrically opposite to each other).

In the experiment, we need to produce a parallel beam of rays to be incident on the prism. This is done with the help of a collimator. The collimator has an adjustable rectangular slit at one end and a convex lens at the other end. When the illuminated slit is located at the focus of the lens (See Fig. 1), a parallel beam of rays emerges from the collimator. We can test this point, with the help of a telescope adjusted to receive parallel rays. We first prepare the telescope towards this purpose as follows:

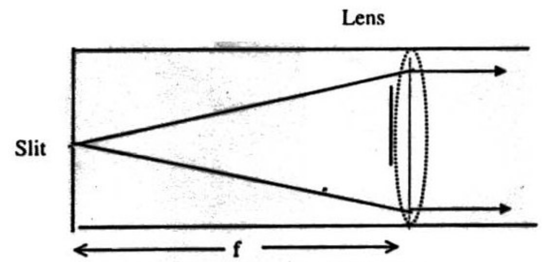


Fig : 1 Collimator

- **Setting the eyepiece:** Focus the eyepiece of the telescope on its cross-wires (for viewing the crosswires against a white background such as a wall) such that a distinct image of the crosswire is seen by you. In this context, remember that the human eye has an average "least distance of distinct vision" of about 25 cm. When you have completed the above eyepiece adjustment, you have apparently got the image of the crosswire located at a distance comfortable for your eyes. Henceforth do not disturb the eyepiece.

- **Setting the Telescope:** Focus the telescope onto a distant (infinity!) object. Focusing is done by changing the seperation between the objective and the eyepiece of the telescope. Test for the absence of a parallax between the image of the distant object and the vertical crosswire. *Parallex effect (i.e. separation of two things when you move your head across horizontally) exits, if the cross-wire and the image of the distant object are not at the same distance from your eyes.* Now the telescope is adjusted for receiving parallel rays. Henceforth do not disturb the telescope focusing adjustment.

- **Setting the Collimator:** Use the telescope for viewing the illuminated slit through the collimator and adjust the collimator (changing the separation between its lens and slit) till the image of the slit is brought to the plane of crosswires as judged by the absence of parallax between the image of the slit and crosswires.

- **Optical leveling of the Prism:**
  The prism table would have been nearly leveled before use have started the experiment. However, for your experiment, you need to do a bit of leveling using reflected rays. For this purpose, place the table with one apex at the center and facing the collimator, with the ground (non-transparent) face perpendicular to the collimator axis and away from collimator. Slightly adjust the prism so that the beam of light from the collimator falls on the two reflecting faces symmetrically (Fig. 2) When you have achieved this lock the prism table in this position. Turn the telescope to one side so as to receive the reflected image of the slit centrally into the field of view. This may be achieved by using one of the leveling screws. The image must be central whichever face is used as the reflecting face. Similarly, repeat this procedure for the other side.

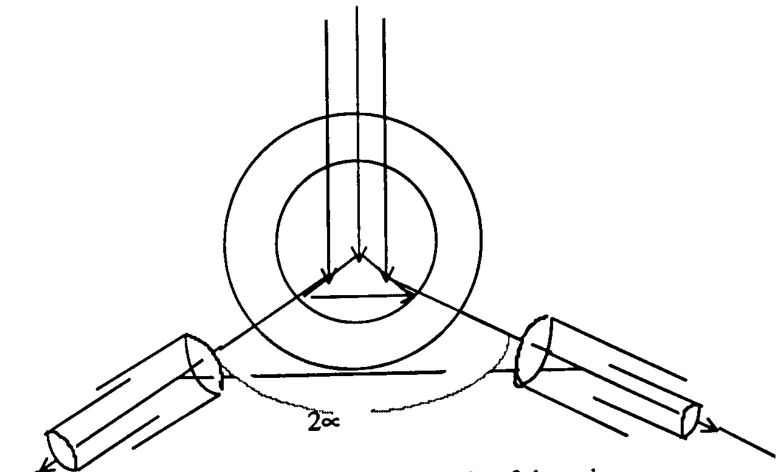


Fig : 2 Experimental set-up :angle of the prism

- **Finding the angle of the prism (α)**:

With the slit width narrowed down sufficiently and prism table leveled, lock the prism table and note the angular position of the telescope when one of the reflected images coincides with the crosswires. Repeat this for the reflected image on the otherside (without disturbing the prism and prism table). The difference in these two angular positions gives 2α.

- **Finding angle of minimum deviation (δ_m):**

Unlock the prism table for the measurement of the angle of minimum deviation (δ_m). Locate the image of the slit after refraction through the prism as shown in Fig. 3. Keeping the image always in the field of view, rotate the prism table till the position where the deviation of the image of the slit is smallest. At this position, the image will go backward, even when you keep rotating the prism table in the same direction. Lock both the telescope and the prism table and to use the fine adjustment screw for finer settings. Note the angular position of the prism. In this position the prism is set for minimum deviation. Without disturbing the prism table, remove the prism and turn the telescope (now unlock it) towards the direct rays from the collimator. Note the scale reading of this position. The angle of the minimum angular deviation, viz, δ_m is the difference between the readings for these last two settings.

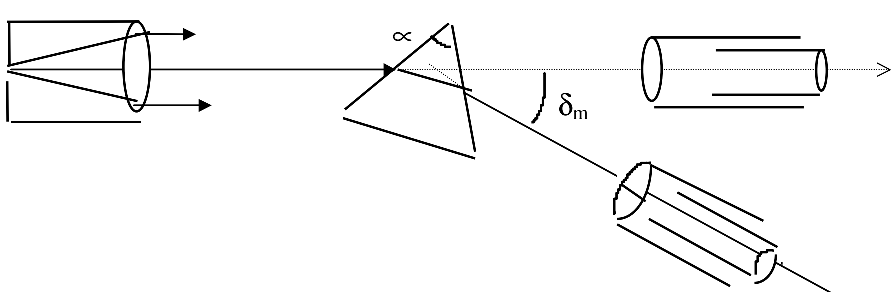


Fig 3. Minimum deviation geometry

Observation tables:

1. For angle of the prism:

Vernier A				Vernier B			
Telescope Reading		2α	α	Telescope Reading		2α	α
Face I	Face II			Face I	Face II		

2. For angle of minimum deviation:

Vernier A			Vernier B		
Direct Reading	Minimum Deviation	δ_m	Direct Reading	Minimum Deviation	δ_m

Calculation:

Use eqn. (3) to calculate the speed of light in the glass medium.

Result:

Sped of light in glass = ……..

References:

1. F. A. Jenkins and H. F. White, "Fundamentals of Optics" (McGraw Hill, 1981), *Chapter 2.*
2. E. Hecht and A. Zajac, "Optics", (Addision Wesley, 2nd Ed. 1987).

Experiment 25

Polarization of light

Apparatus
Laser source, polarizer, analyzer, photodiode, battery, multimeter, glass slab, optical table and stand.

Objective

To study the polarization of light, to verify Malus law and to find the Brewster angle for glass.

Theory

There are a number of ways an unpolarised light can be converted into a plane polarized light. You are given two polarising sheets (polaroids). The light passing out of a polarizer is linearly polarized with the electric field E fixed in one direction in space as determined by the orientation of the polarizing sheet. If this light passes through a second polarizer (analyser), then the light output depends on the relative orientation of the two polarizers. If the pass plane of the second polarizer is making an angle θ with respect to the electric field E, then the magnitude of the field in the output wave is $\cos\theta$ and the output intensity is proportional to $\cos^2\theta$ Thus the output intensity I of the light transmitted by the analyser is given by

$$I=I_0 \cos^2\theta \qquad (1)$$

Where I_0 is the intensity of the polarized light incident on analyser. This is known as Malus law.

Alternatively one can obtain polarised light by using a beam that is reflected at an interface at a particular angle called Brewster angle.

Consider a polarised beam falling on an interface YZ (fig. 1). The beam is in XY plane and the polarisation of the light is in the plane of incidence (electric field E_I is in XY plane) . The magnitude of the reflected electric field is given by

$$E_R = \left(\frac{\alpha-\beta}{\alpha+\beta}\right)E_I \qquad (2)$$

Where $\alpha = \cos\theta_T/\cos\theta_I$ and $\beta = \mu_1 n_1/\mu_2 n_2$. μ is the magnetic permeability of the material and n is the refractive index of the material.

Thus the reflectivity (E_R/E_I) depends on angle of incidence for the inplane polarisiation and goes to zero at a certain angle of incidence called Brewster angle θ_B given by

$\tan\theta_B = n_1/n_2$

This fact can be used to get a polarised beam from an unpolarised beam. An unpolarised beam is made to incident at an interface at Brewster angle. The reflected beam will contain the perpendicular component only.

Experimental Setup

The set-up consists of a laser light source (partially polarised), polariser, analyser, and a photodiode (Fig. 2). The analyser unit is fitted with a circular scale to record the angular readings. Photodiode is used to measure the intensity of light. All the components can be mounted on an optical bench for proper alignment

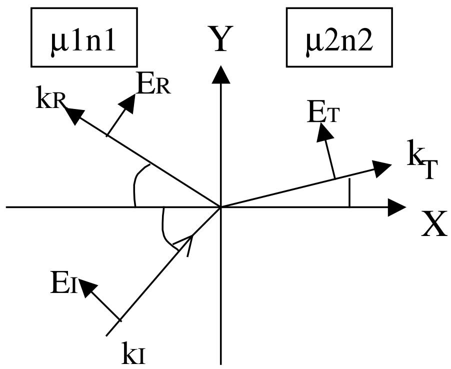


Fig. 1

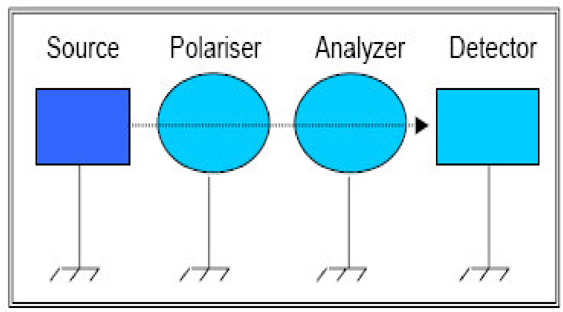


Fig. 2

Procedure

Part A

1. Assemble the photodiode circuit (reverse bias) in photoconductive mode as shown in fig 3. In this configuration photocurrent will be directly proportional to the intensity of light falling on to it.
2. Align the light source and two polaroid sheets so that the beam passes through both the polarisers and falls on to the detector. The plane of polaroids must be perpendicular to the beam.
3. Remove the polariser from the path of the beam and rotate the analyser to get the maximum photocurrent (as the source is partially polarised). Now insert the polariser in between laser and the analyser and rotate ithe polariser to get again maximum current. This will ensure that the pass plane of polariser and analyser are parallel and along the larger component of the field.
4. Now rotate the analyser in small angular steps and record the photocurrent current as a function of θ.

Part B

1. Remove the polariser from the path of the beam.
2. Place the glass slab on a horizontal table and align it with light source so that the incident beam is normal to the glass surface. Note this angular reading. Angle of incidence can be changed by rotating the glass plate about vertical axis.
3. Set the analyser such that it passes only horizontal polarised light.
4. Record the intensity of reflacted beam as a function of angle of incidence.

Observation Table:

Part A: θ = angle between Polaroid sheet

I_T= Total current

I_S=Stray light current

Table I

S. no.	θ (degree)	I_T (mV)	I_S (mV)	$I=I_T-I_S$
1	0			
2	5			
3	10			
..	..			
..	..			
..	360			

Part B: θ_I = Angle of incidence

Table II

S. No.	θ_I (degree)	I_T (mV)	I_S (mv)	$I=I_T-I_S$
1	10			
2	15			
3	20			
4	25			
5	30			
6	35			
7	40			
8	45			
9	50			
10	52			
11	54			
12	56			
13	58			
14	60			
15	65			
16	70			
17	75			
18	80			

Analysis:

1. In Part A, plot I vs. θ and verify eqn. (1).
1. In Part B, plot I vs. θ_I. Find Brewster angle from the minima of the graph. Estimate uncertainty in the Brewster angle.

For calculating error in θ_B *i.e.* $\Delta\theta_B$ from graph, use the following concept:

$\Delta\theta_B = \Delta\theta_{I_{\min}} + \Delta\theta(\Delta I)$, where ΔI is the least count in I measuring instrument.

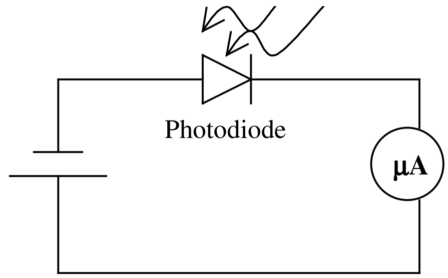


Fig. 3

Results:

Brewster's angle for glass = ………………………….

(Two graph papers required).

Reference: F. A. Jenkins and H. F. White, "Fundamentals of Optics" (McGraw Hill, 1981), *Chapter 24.*