

# PHYSICS LABORATORY MANUAL

For Undergraduates  
2016-17

**The LNM Institute of Information Technology**  
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# Laboratory Regulations

1. Attendance is compulsory and it carries **10% weightage** on grade evaluation for this course.
2. Students should be punctual. They will be marked absent if they are not present within the first five minutes of each laboratory session.
3. Experiments will be performed in groups defined by the lab instructors. Students are not allowed to change their partner during the semester under any circumstance.
4. It is **compulsory** to bring the lab manual and required graph papers. The lab register will be kept in the laboratory and students are not supposed to carry the lab register with them after completion of the experiment. Such activities will be penalized.
5. Pre-recorded audio visual demo for every experiment will be sent to you in due time. Prior to performing each experiment, you should be familiar with the basic principles from them. **There will be no additional demo for any of the experiment will be given during the lab session.**
6. During each lab session you are expected to perform the experiment, record the observed data in your lab register (**not** in any rough note book) and complete the experiment including the written record. For each experiment, you have to write in your lab register the **purpose, description of apparatus, working formula** (if any), and **tables** for observations.
7. Students are supposed to handle the instruments carefully. In case of any technical difficulty take help from the lab attendant. After performing the experiment hand over the instrument(s)/components and or switch off (in case of electrical devices) properly. Any intentional manhandling of any experimental set ups will lead to disbaring of the student from the subsequent lab sessions depending on the severity.
8. Student while performing the experiments are supposed to get a few readings signed by the respective instructor or TA in their lab register.
9. The lab register completed in all respects should be submitted at the end of each lab session (take a note of the point4 above).
10. Laboratory evaluation will also depend on satisfactory performance in the viva which will be conducted for each experiment.
11. The student is expected to be in the lab for the entire 3 hours. Leaving the laboratory early without informing is liable for deduction in class performance marks.

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# A. Measurement & Instruments

This section of the manual describes the basic measurements and allied instruments that you will encounter in the laboratory.

## Physical Measurements

In the grouping of physical measurements the quantities to be measured are length, mass, angle and time.

### Length

There are three basic instruments for the measurement of length, (i) the meter ruler, (ii) the micrometer screw gauge and (iii) the vernier calipers. The table below details the range and accuracy of these three instruments.

Name	Range	Accuracy
Meter Ruler	0 – 100 cm	1 mm
Micrometer Screw Gauge	0 – 25 mm	0.01 mm
Vernier Calipers	0 – 150 mm	0.02 mm

Clearly, there is a wide variation in the range of the instruments and the first lesson is that the choice of instrument is determined by the length that is to be measured. If the length is  $50\text{cm}$ , then it clearly should be the Metre Ruler. The second lesson concerns the accuracy. In principle, you can measure a length of  $2\text{cm}$  with all three instruments but the accuracy of your measurement will vary from  $1\text{mm}$  to  $0.01\text{mm}$ . The choice, then, is also determined by the accuracy required. The accuracy of an instrument depends on its construction & operation and this is now described for each instrument

**Meter ruler:** The principle of the metre ruler is very simple. A known length (1 metre) is divided into 100 unit lengths of  $1\text{cm}$ . and these are further subdivided into 10 unit lengths of  $1\text{mm}$ . The accuracy of the instrument is the smallest division, namely  $1\text{mm}$ .

*Operation:* Place one end of the ruler (or an appropriate ‘zero’) at one end of the length to be measured and read off the nearest value at the other end of the length to be measured.

**Micrometer screw gauge:** The principle of the micrometer is the screw thread. The pitch of the screw is  $0.5\text{mm}$ . that is one complete rotation of the screw advances or retracts the screw by  $0.5\text{mm}$ . Underneath the rotating barrel of the gauge is a ruler with  $0.5\text{mm}$  divisions (actually two sets of  $1\text{mm}$  divisions offset by  $0.5\text{mm}$ ). The rotating barrel is itself subdivided into 50 units, such that rotation of the barrel through one unit advances or retracts the screw by  $0.5/50 = 0.01\text{mm}$ ; the accuracy of the instrument is therefore  $0.01\text{mm}$ .

*Operation:* Place the object between the fixed and moving end faces and rotate the barrel until the object is in contact with both end faces. **Always rotate using the small slip knob at the end of the barrel.** This will ensure contact without damage to the object or the micrometer. The measured length is the reading on the ruler to the nearest full  $0.5\text{mm}$  unit **plus** the portion of this unit shown on the rotating barrel. *Always check the visible zero setting and all for any offset from zero.*

**Vernier calipers:** The principle of the Vernier calipers is two-fold. First, the sliding piece allows the jaws to contact the sides of the object to be measured, in much the same way as the micrometer. The distance moved by the sliding jaw is then read off the fixed ruler on the main body of the instrument. The accuracy of that ruler as such, however, is only  $1\text{mm}$ . The much improved accuracy is provided by the 'Vernier' scale. This scale is marked on the sliding jaw; it has 10 divisions, each subdivided into 5, ie a total of 50 subdivisions. These subdivisions look like  $1\text{mm}$  in length. But if you compare the fixed and Vernier scales, you will see that the 50 subdivisions on the Vernier scale correspond to 49 subdivisions (each of  $1\text{mm}$ ) on the fixed scale! This is not a mistake but rather it is deliberately designed so that a subdivision on the Vernier scale is smaller than that on the fixed scale by  $1/50 = 0.02\text{mm}$ ; this is the accuracy of the instrument. How a reading with this accuracy is achieved in practice is detailed below:

*Operation:* With **no** object between the jaws, the zeros of the Vernier and fixed scales are coincident. There is an increasing mismatch between the marks of these two scales until at the end of the Vernier scale there is again coincidence between the end mark on the Vernier and the  $49\text{mm}$  mark on the fixed scale. Clearly, to obtain coincidence between the first subdivisions of the Vernier and of the fixed scales it would be necessary to move the sliding jaw by the deficit of  $0.02\text{mm}$ ; coincidence between the second subdivisions would require  $2 \times 0.02 = 0.04\text{mm}$ , and so on. A total of  $50 \times 0.02 = 1\text{mm}$  is required to achieve coincidence between the end mark of the Vernier scale and the  $50\text{mm}$  mark of the fixed scale. Conversely, a measurement of the length of an object in contact with the jaws is the reading to the nearest full mm on the fixed scale at the Vernier zero **PLUS** the reading (in units of  $0.02\text{mm}$ ) on the Vernier scale **where there is coincidence between the vernier and fixed scales.**

**Other vernier instruments:** There are three other instruments in the laboratory which incorporate Vernier scales. These are the travelling microscope, the weighing scales and the spectrometer. The travelling microscope combines magnified optical positioning with a ruler accuracy of  $0.01\text{mm}$ .

For the other two instruments some other parameter has been equated with a length scale.

In the case of the weighing scales, mass can be equated with the length of the balance arm that is divided into 10 units of  $10\text{g}$ . The rotating scale adds up to a further  $10\text{g}$  with an accuracy of  $0.1\text{g}$  and the Vernier scale accuracy is  $0.01\text{g}$ .

In the case of the spectrometer, angle can be equated with the length of a circular scale that has an accuracy of  $0.5$  degree. The Vernier scale is in the natural sub-unit of *minutes of arc* ( $60$  minutes of arc =  $1$  degree) and the accuracy is one minute of arc ( $1'$ ).

## Time

The stop-clock has a start/stop/reset push-button device with a digital display. In principle, the accuracy is the smallest digit, ie  $0.01\text{s}$ , but the response time of the button is of the order of  $0.1\text{s}$  and that of the user may be significantly longer, say, of the order of  $1\text{s}$ . Timing accuracy is further discussed later in the section Accuracy & Uncertainty.

## Electrical Measurements

In the grouping of electrical measurements, the principal instruments are the multimeter, oscilloscope, function generator and the power supply.

### Multimeter

The multimeter provides conveniently in a single instrument a number of ranges of measurement of voltage (DC/AC), current and resistance. It is necessary to select the appropriate quantity and range as well as the proper connections for the two input leads. *The AC ranges are distinguished from the DC ranges by the symbol ( $\sim$ ).*

**Voltage:** The voltage ranges are marked  $V$ . The two input sockets are marked COM and  $V, \Omega$ .

Voltage is measured *across* a component, that is, the meter is connected *in parallel* with the component. *The meter displays the polarity of the voltage relative to the COM connection.*

**Current:** The current ranges are marked  $A$ . The two input sockets are marked COM and either  $A$  or  $10A$ , depending on the magnitude to be measured; the  $A$  connection is protected by a *2amp* fuse and is only to be used for currents less than this limit. The  $10A$  connection is protected by a *10amp* fuse, and is only to be used for currents up to this limit. *This latter connection only works with the current range marked 10.*

Current is measured *through* a component, that is the meter is connected *in series* with the component. *The meter displays the polarity of the current entering the  $A$  (or  $10A$ ) socket.*

**Resistance:** The resistance ranges are marked  $\Omega$ . The two input sockets are marked COM and  $V, \Omega$ .

Resistance is measured *across* a component, that is, the meter is connected *in parallel* with the component. There is no polarity associated with this measurement.

It is important to realize that resistance measurement is really the measurement of the voltage resulting from a current supplied by the meter. *Therefore, this mode of resistance measurement cannot be carried out on components while they are in circuit.*

**Range & display:** The maximum display of 1999 corresponds to the end of the range selected. For example, selecting the voltage range marked 2 allows a measurement of voltage up to 1.999 volts. The next voltage range is marked 20. This range is appropriate for voltage between 2 and 20 volts.

The accuracy of the measurement is the least significant digit (note how this digit may arbitrarily change up or down by one unit during the reading). *The best practice is to use the range which is one setting above that at which the full 1999 shows.*

### Oscilloscope, function generator & power supply

The oscilloscope is probably the most important of all electronic measuring equipment. Its main use is to display on a screen the variation or a potential difference (or voltage) as, a function of time. The result is a graph with voltage on the vertical (or  $y$ ) axis and time along the horizontal (or  $x$ ) axis. This is achieved by electrostatic deflection of an electron beam striking the front face phosphor in the cathode ray tube in the oscilloscope.

*You will learn about oscilloscope, function generator and power supply in your electronics laboratory.*

## Plotting graphs

A graph is a useful way of displaying the results of an experiment in which one parameter (call it  $x$ ) is varied in well defined steps and another parameter (call it  $y$ ) is measured in response. In this general case each  $(x, y)$  pair of values is represented by a point which is a distance  $x$  along the horizontal axis and a distance  $y$  along the vertical axis. For example, if the following data were obtained for the resistance of varying lengths of wire:

L (m)	1	2	3	4
R ( $\Omega$ )	10	20	30	40

The data would be graphed as shown below:

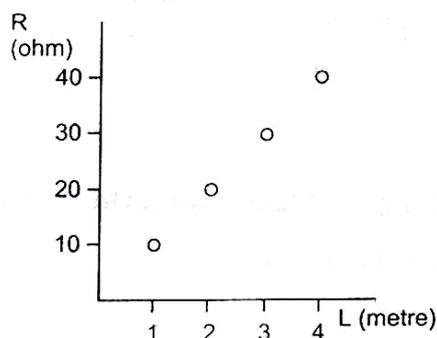


Figure 1: Resistance (R) vs Length (L)

Note the title, the labeled axes (with units!). These elements are essential for any graph! The usefulness of this particular graph is that it is clear at a glance that the resistance of the wire is proportional to its length. This is formally shown in the graph below where the data fall on a straight line through the origin.

Mathematically, this linear relation is expressed by the equation  $y = mx$ , where  $m$  is the slope. The slope of the straight line is obtained by constructing a right-angle triangle containing the straight line and lines parallel to the vertical and horizontal axes; the slope is the ratio of the lengths of the vertical and horizontal sides (shown dashed below). Note that for good accuracy the complete range of plotted data should be used.

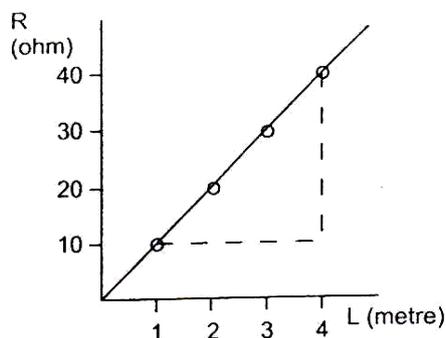


Figure 2: Resistance (R) vs Length (L) showing slope

In this particular example the slope is  $(40-10)/(4-1) = 30/3 = 10$ . The resistance per unit length of the wire is 10 ohm per metre or simply  $10\Omega m^{-1}$ . (In shorthand  $R(\Omega) = 10\Omega m^{-1}L(m)$ ).

This trivial example has been used to introduce you to the basics of graph plotting. Only rarely will your experimental data be in this ready-to-graph form. For example,

consider the following measurements of the resistance versus the temperature of a fixed length of the wire:

T ( $^{\circ}C$ )	100	200	300	400
R ( $\Omega$ )	34	36	38	40

The data could be plotted as shown in Fig. 3. This time, the straight line does not

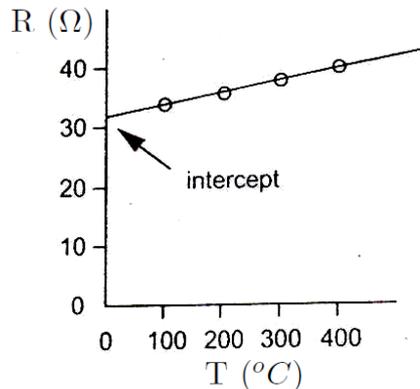


Figure 3: Resistance (R) vs Temperature (T)

go through the origin and the mathematical expression is  $y = mx + C$ , where  $C$  is the intercept on the  $y$  axis. In this case the intercept,  $C$  is  $32\Omega$  and the slope,  $m$  is  $2\Omega^{\circ}C^{-1}$ . We can therefore write  $R(\Omega) = 2(\Omega^{\circ}C^{-1})T(^{\circ}C) + 32\Omega$ .

This example also illustrates an important value judgment about the axes of a graph. As drawn above most of the graph page is wasted. A better graph (and a more accurate one) is shown in figure on next page. The origin is now the point  $(30, 0)$  rather than  $(0,$

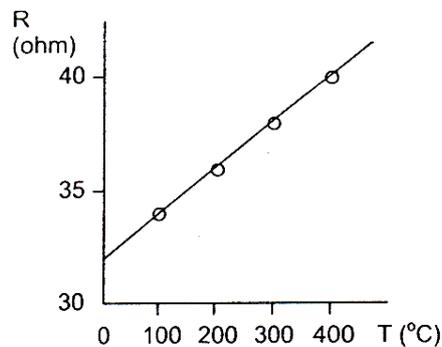


Figure 4: Resistance (R) vs Temperature (T)

$0)$  and the labeling must show that clearly! Clearly the choice is dictated by whether the intercept is to be determined. Also, the intercept of interest may be on the horizontal (or  $x$ ) axis. These considerations apart, you should always aim to use the full size of the available graph page.

What to do with a system which is not in linear form? A good example is the relation between period ( $T$ ) of a simple pendulum and its length ( $L$ ). These are related by the expression . When we plot a graph of  $T$  vs  $L$  we get a curve. But if we plot a graph of  $T^2$  vs  $L$ , we should get a straight line of the form  $y = mx$ . That is, we re-write the expression in the form of a straight line as  $T^2 = (4\pi^2/g)L$ . In this way it is clear if our data matches the theory. Moreover, from the measurement of the slope  $m$  we obtain a value of  $g = 4\pi^2/m$ .

Finally, it is useful to start thinking of a graph as a way of *averaging* your data and this concept will be fully discussed in the next section on Accuracy and Uncertainty.

## Accuracy and uncertainty (and errors!)

A physical measurement is never exact. Its accuracy is always limited by the nature of the apparatus used, the skill of the person using it and other factors. The best we can do is report a range of values, so there remains some uncertainty. So typically we may write: *The velocity of the ball was found to be  $5.13 \pm 0.02 \text{ms}^{-1}$ . This defines the range 5.11 to 5.15.*

The end points of the range can rarely be assigned with much precision (in this laboratory, at least), so if a calculated estimate of the uncertainty were to give us 0.018732 in the above, we would make it 0.02, retaining just a single significant figure. We must also trim the digits of the main (central) value to the same point so that 5.128765 become 5.13 in the stated result.

The three rules for a measured (or calculated) value are:

- Include the uncertainty estimate to one significant figure.
- Trim the digits of the value to the same significant figure.
- Don't forget the units.

*How do we estimate uncertainty?* In the case of most\* individual measurements it arises naturally from the fact that the instrument has a printed scale (\*special cases are discussed later!). A reasonable estimate of the uncertainty is plus-or-minus half the interval of the scale, if you use it straightforwardly. In the case of modern instruments with an electronic display, there may be a stated limit to the accuracy. In some such cases, if you try to read out more digits the ones at the end will fluctuate, telling you they are unreliable.

***To keep things simple it is recommended that you use plus-or-minus the smallest interval of the scale.***

But this is the start of a long story of statistics, to which we will pay little attention now. We will use our common sense and some very elementary mathematics. The mathematical rules follow in a separate section. Remember they are intended for rough-and-ready estimates—don't labour over enormous calculations—use short cuts and mental arithmetic whenever you can. If the person on the next bench gets  $\pm 0.2$  and you get  $\pm 0.3$ , it's unlikely to matter at all. Do it quickly.

### FAQ on uncertainty and errors

1. ***Isn't uncertainty called error?***

Yes, it often is, alas. In fact it's quite traditional. The unfortunate thing is that it makes uncertainty sound like a mistake.

2. ***But don't we make mistakes?***

We all do. These will give rise to data points that don't fit into the overall pattern, and can be checked and replaced. That's one reason why we take sets of measurements and fit them to some sort of theory.

3. ***But suppose I keep making the same error, such as using an instrument whose zero has not been set properly, or the wrong units?***

Yes, we are all human. That would be called a systematic error. We've been talking about random errors or uncertainty here. A systematic error is something you usually don't know about, so you cannot state it! If you can, you should be able to eliminate it.

#### 4. *How can I detect a systematic error?*

If experiment does not conform to theoretical expectations, one or the other needs to be improved. In the case of the experiment, search for systematic errors. This dialogue between theory and experiment is how both progress and reliable measurement techniques are developed.

#### 5. *How do I combine the errors from individual measurements?*

There are basic rules for this as outlined below.

### Combining errors of individual measurements

If the measured values of  $A$  and  $B$  have certain uncertainties, what are the consequent uncertainties of  $AB$ ,  $A + B$  and  $\sin(A + B)$ ?

For many, this is the hard part of the subject, but it boils down to a few simple rules and procedures. It is much less painful if you remember precise calculations with rough estimates make little or no sense. Feel free to take short cuts by making rough-and-ready approximations as you go along, in order to arrive quickly at an estimate of the final error.

**Rules:** Here we shall indicate the uncertainty of  $A$  by  $\Delta A$ . That is, the measured range is  $A \pm \Delta A$ .

**Rule 1:** For addition (or subtraction) **add** the uncertainties.

If  $C = A + B$ , or  $C = A - B$ , then  $\Delta C = \Delta A + \Delta B$ .

Example:  $A = 50 \pm 1$ ,  $B = 20 \pm 2$ , then  $A + B = 70 \pm 3$  and  $A - B = 30 \pm 3$

**Rule 2:** For multiplication (or division) **add** the relative uncertainties to get the relative uncertainty of the final quantity.

If  $C = A \times B$ , or  $C = A/B$ , then  $\Delta C/C = \Delta A/A + \Delta B/B$ . Having found this fraction, simply multiply by  $C$  to get  $\Delta C$ !

Example:  $A = 50 \pm 1$ ,  $B = 20 \pm 2$ . For  $C = AB$ ,  $C = 1000 \pm 120$ . for  $C = A/B$ ,  $C = 2.5 \pm 0.3$

Note that, in particular, If  $C = 1/A$ , then  $\Delta C/C = \Delta A/A$ .

**Rule 3:** Dealing with functions.

There are two ways of dealing with functions, such as  $C = \sin(A)$  or  $C = \exp(A)$ . One can express the uncertainty in terms of the derivative of the function. Perhaps you can see the logic of this. But a more straight forward approach, which should almost always work, is as follows.

*Work out the values of the function for  $A + \Delta A$  and  $A - \Delta A$ , and take these to define the range of values of the function  $C$ .*

All of these rules can easily be justified by elementary mathematics, *provided that the relative uncertainties are small.*

### Four special cases:

#### 1. *Judgement errors*

These arise in cases where the experimenter has to make a judgement about when some condition is fulfilled in location or in time. Once the location or time is fixed it can be measured to a certain accuracy or error. However, this error may be much

less than the error associated with the judgement. A good example is the location of the viewing screen in the experiment on the convex lens. The experimenter has to make the judgement when the image on the screen is *in focus* and the error in position associated with this judgement may be much larger than the measurement error of the emphfinal position. The real error has to be estimated by gauging the range of position over which the image appears to be still *in focus*.

### 2. *Improving the timing error in a periodic system*

The error associated with a single measurement can be dramatically reduced by measuring the combination of many identical units. A good example of this is the measurement of the period of a pendulum. Suppose the measurement of a single swing is  $20 \pm 1s$  (where the error of 1 includes the judgement error of when the swing starts and ends). The total time for 10 swings of the pendulum might be  $195s$  but the error in this measurement would still be  $1s$ . The period would be  $(195 \pm 1)/10$  or  $19.5 \pm 0.1s$ . The latter is a more accurate result.

### 3. *Improving the count rate error in a "random emission" system*

Radioactive emission is random in time. This means that repeated measurement of the emission, usually called *the count* in fixed periods of time shows a range of values (or error) which is related to the size of the count. The mathematics behind this is quite complex but the result is very simple: *The error in the count is the square root of the count!* For example, if the count is 100, the error is  $\sqrt{100} = 10$ , answer  $100 \pm 10$ . Now, suppose this count is taken in a time of  $1s$ . Ignoring any error in the time, the count rate (as opposed to the count) is clearly  $100 \pm 10s^{-1}$ . However, counting for the longer time of 10 s might yield a total count of 1020; the associated error is  $\sqrt{1020} = 32$ , i.e. the total count is  $1020 \pm 32$ . The count rate is  $(1020 \pm 32)/10 = 102 \pm 3$ . The latter is a more accurate result!

### 4. *Average values of non-uniform parameter*

Suppose you need to measure the diameter of a ball. A single measurement will yield a value and associated error. However, a physical ball is not a perfect sphere and a measurement of diameter at another orientation may yield a different result. The more useful value of diameter is the average value estimated from a number of measurements. Suppose the following measurements are taken of the diameter:

$25 \pm 1$	$23 \pm 1$	$28 \pm 1$	$22 \pm 1$	$24 \pm 1$	$23 \pm 1$
------------	------------	------------	------------	------------	------------

The average value is clearly  $(25 + 23 + 28 + 22 + 24 + 23)/6 = 145/6 = 24.17$  but what is the error? This question brings us into the area of statistics and there is no easy answer to this other than a full statistical analysis. *One thing is certain: the error in the average is NOT the average of the errors!*

We recommend the following approximate method:

First, examine which is greater, the range of values or the error in any individual, value. In the unlikely event that it is the latter then this is the error in the average! More likely, the range of values is greater, as is the case here; the values range from 22 to 28, a range of 6. A crude estimate of the error is therefore  $\pm 3$ . However, if you think about it, increasing the number of measurements will only increase this estimate of error, whereas the reverse would be the case in a proper statistical analysis. Visual inception of the data above shows that 5 out of the 6 values lie within the range  $24 \pm 2$  and this is a more reasonable answer. *When you encounter this type of error in an average, it is sufficient to make a rough estimate along these lines!*

## B. Error bars on graphs

Whenever you enter data as a data point on a graph, the uncertainty in one or other of the  $x$  and  $y$  values can be indicated by error bars, which show the range of values for that parameter at each data point. This is helpful in judging by eye whether the data is consistent with some theory, or whether some particular measurement should be repeated.

This applies to graphs drawn by hand or by computer. In practice, it may be simplified in many cases. For example, if the relative uncertainty in  $x$  is much less than that in  $y$  – or vice-versa – it is not worth representing the smaller error bar on the graph or it might be that the uncertainty is too small to be visible, in that case there should be a statement on the graph to that effect.

Consider the following modified data set for the resistance versus the temperature of a fixed length of the wire:

T( $^{\circ}$ C)	$100 \pm 1$	$200 \pm 1$	$300 \pm 1$	$400 \pm 1$
R ( $\Omega$ )	$34 \pm 1$	$37 \pm 1$	$38 \pm 1$	$41 \pm 1$

When the bare data is graphed as shown in Fig 5(a) it is not possible to link the points with a straight line. However, when error bars are included for the R values (the error in T is much smaller) then it is possible to put a straight line through the error bars, as shown in Fig 5(b). These data now verify the linear relation. The remaining question is

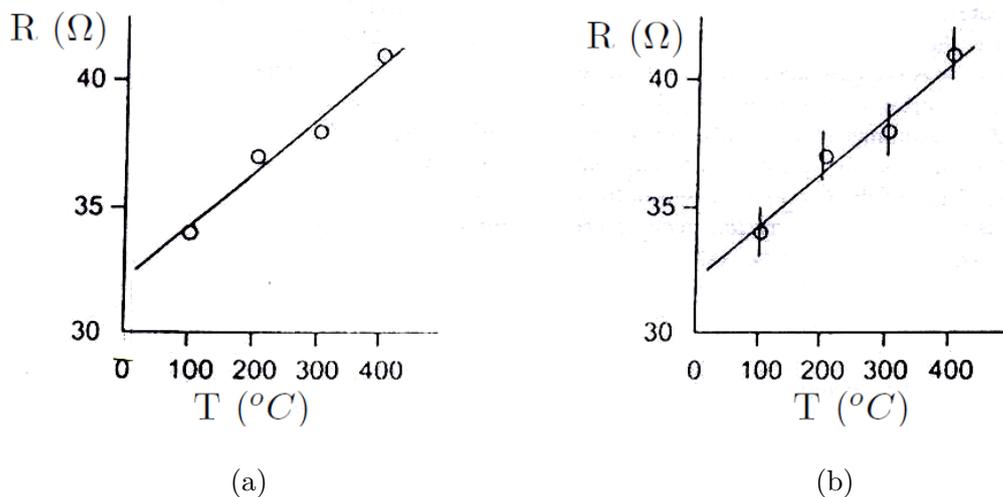


Figure 5: Resistance (R) vs Temperature (T) (a) without error bars and (b) with error bars

which straight line? It is clear that there is a smaller but finite range of lines of different slope which pass through the error bars. This is important if the slope is used to derive some parameter, e. g. a value of  $g$  in the pendulum experiment.

The slope then becomes  $m \pm \Delta m$ . Again, this is another example of the error associated with an average, as discussed above. Again too, it is difficult to be exact about this.

## C. A comment of significant digits

In many cases the uncertainty of a number is not stated explicitly. Instead, the uncertainty is indicated by the number of meaningful digits, or significant figures, in the measured value. If we give the thickness of the cover of this booklet as  $3.94\text{mm}$  which has three significant figures. By this we mean that the first two digits are known to be correct, while the third digit is in the hundredths place, so the uncertainty is about  $0.01\text{mm}$ . Two values with the same number of significant figures may have different uncertainty, a distance given as  $253\text{km}$  also has three significant figures, but the uncertainty is about  $1\text{km}$ . When you use the numbers having uncertainties to compute other numbers, the computed numbers are also uncertain.

Suppose you measured the mass of a rock to be  $8.2\text{ gm}$  and its volume to be  $2.3\text{ cm}^3$ . How accurately can you determine its density?

Mass measured to 2 significant digits

Volume measured to 2 significant digits

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{8.2\text{ gm}}{2.3\text{ cm}^3} = 3.56521739\frac{\text{ gm}}{\text{ cm}^3}$$

What's wrong with this calculation?  
Not science, but fiction!

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{8.2\text{ gm}}{2.3\text{ cm}^3} = 3.57\frac{\text{ gm}}{\text{ cm}^3}$$

Maybe this doesn't look as impressive, but it is a better answer.

$$\text{Density} = 3.6\frac{\text{ gm}}{\text{ cm}^3}$$

No fictional digits - well, maybe the 7 is stretching it. It is reasonable to carry an extra digit or two in intermediate calculations.

It is better to keep only the number of digits of your weakest measurement for your final answer.

When we add and subtract numbers, it is the location of the decimal point that matters, not the number of significant figures. For example  $123.62 + 8.9 = 132.5$ .

Although  $123.62$  has an uncertainty of about  $0.01$  and  $8.9$  has an uncertainty of about  $0.1$ , so their sum has an uncertainty of about  $0.1$  and should be written as  $132.5$  and not  $132.52$ .

### Exercise:

1. State the number of significant figures:
  - (a)  $0.43$
  - (b)  $2.42 \times 10^2$
  - (c)  $6.467 \times 10^{-3}$
  - (d)  $0.029$

(e) 0.0003

2. A rectangular piece of iron is  $(3.70 \pm 0.01) \text{ cm}$  long and  $(2.30 \pm 0.01) \text{ cm}$  wide. Calculate the area.
3. Mass of the planet Saturn is  $5.69 \times 10^{26} \text{ kg}$  and its radius is  $6.6 \times 10^7 \text{ m}$ . Calculate its density.
4. Estimate the percent error in measuring
  - (a) A distance of about  $56 \text{ cm}$  with a meter stick.
  - (b) mass of about  $16 \text{ g}$  with a chemical balance.
  - (c) A time interval of about 4 min with a stop watch.
5.  $3.1416 \times 2.34 \times 0.58 =$
6.  $2.56 + 16.4329 =$
7.  $16.4329 - 2.56 =$

# D. Vernier caliper & Screw Gauge

Vernier caliper and screw gauge are used for measuring small lengths with precision.

## Vernier caliper

### Parts of the instrument<sup>1</sup>

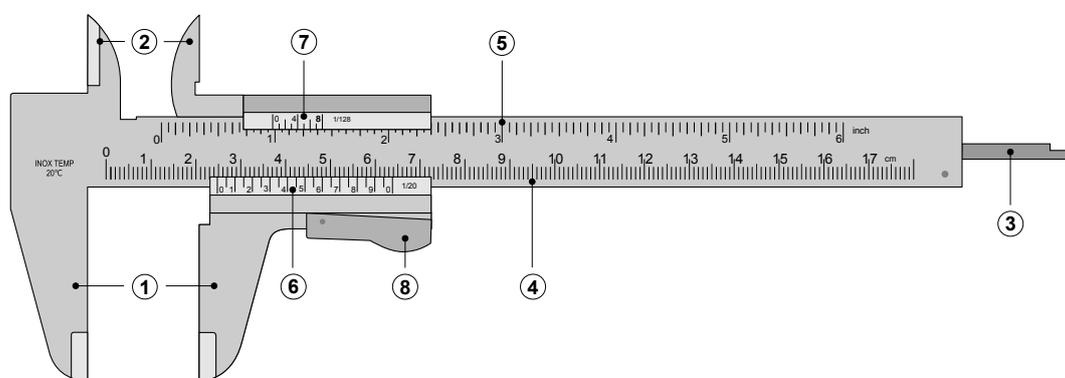


Figure 6: Parts of a vernier caliper

The parts of the calliper include:

1. Outside large jaws: used to measure external diameter or width of an object
2. Inside small jaws: used to measure internal diameter of an object
3. Depth probe: used to measure depths of an object or a hole
4. Main scale: scale marked every mm
5. Main scale: scale marked in inches and fractions
6. Vernier scale gives interpolated measurements to 0.1 mm or better
7. Vernier scale gives interpolated measurements in fractions of an inch
8. Screw/ Retainer: used to block movable part to allow the easy transferring of a measurement.

### Least count of the instrument

The least count is the smallest length you can measure with the help of the instrument. For vernier caliper the least count is defined as

$$\text{Least count (LC)} = \frac{\text{Least count of main scale}}{\text{Number of divisions on vernier scale}}$$

<sup>1</sup>Image source: <https://en.wikipedia.org/wiki/Calipers>

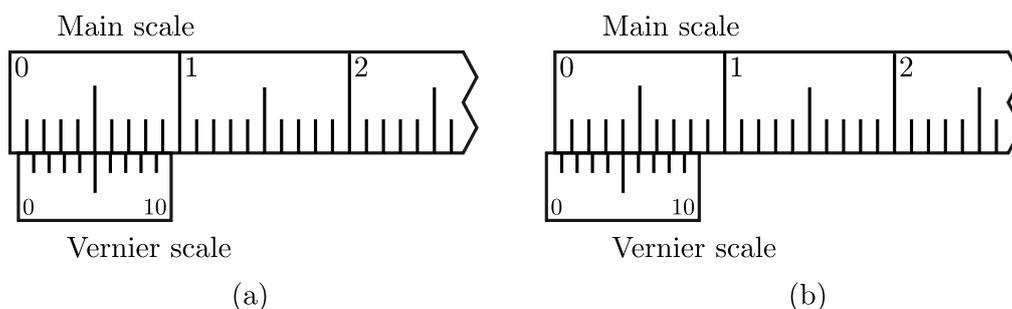


Figure 7: (a) Positive zero error in vernier caliper. (b) Negative zero error in vernier caliper.

### Measurement with the instrument

1. The outer jaws of the vernier caliper should be closed. In this position the zero of the main scale should coincide with the zero of the vernier scale. If this is not the case, then zero error correction has to be applied for each reading.
2. Loosen the screw and place the object to be measured in between the outer jaws. Tighten the screw again so that the scale does not slide.
3. Note down the position of the zero mark on the main scale. Let it be MSR (Main Scale Reading).
4. Note down the position of the vernier scale division which coincides with the main scale division. Let it be VSR (Vernier Scale Reading).
5. The total length of the object is then

$$\text{Length} = \text{MSR} + \text{VSR} \times \text{LC} \quad (1)$$

6. Repeat the steps 2-5 couple of times and take the average of the measured length.
7. Make sure to include proper units and zero correction if required.

### Zero error<sup>2</sup>

Zero errors often arise due to fault in manufacturing. There are two types of zero errors.

#### Positive zero error

If the zero on the vernier scale is to the **right** of the main scale, then the error is said to be **positive** zero error and so the zero correction should be **subtracted** from the reading which is measured. See Fig. 7(a).

#### Negative zero error

If the zero on the vernier scale is to the **left** of the main scale, then the error is said to be **negative** zero error and so the zero correction should be **added** from the reading which is measured. See Fig. 7(b)

<sup>2</sup>Image source: <http://educationsight.blogspot.in/2014/02/vernier-zero-error-and-its-correction.html>

## Measurement principle of vernier scale

First of all consider the Fig. 8(a) where the diameter of an object needs to be measured with the main scale which has least count (LC) of 1 mm. Since the diameter of the object is exactly 5 mm there is no need of the vernier scale.

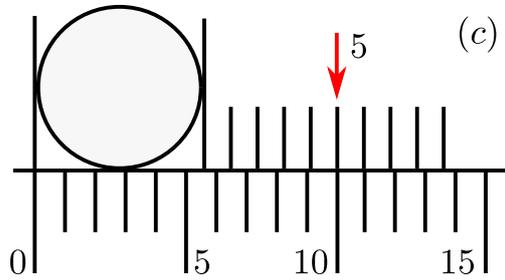
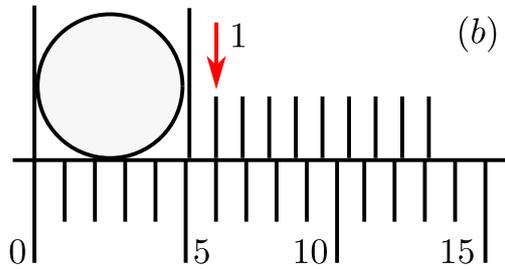
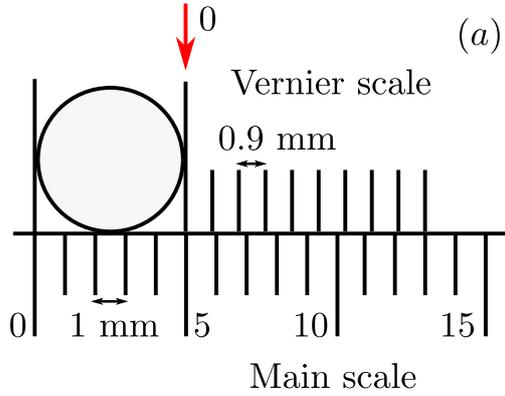


Figure 8: Vernier measurement

Now consider Fig. 8(b), where main scale reading shows the diameter of the object is slightly bigger than 5 mm which can not be measured by main scale alone. Here, vernier scale plays an important role. If you watch closely the vernier scale you will find a vernier division is slightly smaller than the main scale division. In the present example,

$$\begin{aligned} 10 \text{ Vernier Scale Divisions (VSD)} \\ = 9 \text{ Main Scale Divisions (MSD)} \end{aligned}$$

Least count is therefore

$$\begin{aligned} \text{LC} &= 1 \text{ MSD} - 1 \text{ VSD} \\ &= 1 \text{ MSD} - \frac{9}{10} \text{ MSD} \\ &= 0.1 \text{ MSD} = 0.1 \text{ mm} \end{aligned}$$

Therefore the diameter of the object being measured in Fig. 8(b) is

$$\begin{aligned} D &= 5 \text{ mm} + (1 \text{ MSD} - 1 \text{ VSD}) \\ \text{therefore } D &= 5.1 \text{ mm} \end{aligned}$$

Now, to generalize the concept, consider Fig. 8(c). In this case the diameter of the object is slightly bigger than the previous case. To measure this extra length, vernier constant can again be utilized. If the fifth division matches with one of the main scale division that means the extra distance over and above 5 mm is equal to  $5 \times \text{LC}$ . So the generalized formula for measurement would be

$$D = \text{MSR} + \text{VSR} \times \text{LC}$$

where MSR is the Main Scale Reading and VSR is the Vernier Scale Reading.

# Screw Gauge

## Parts of the instrument<sup>3</sup>

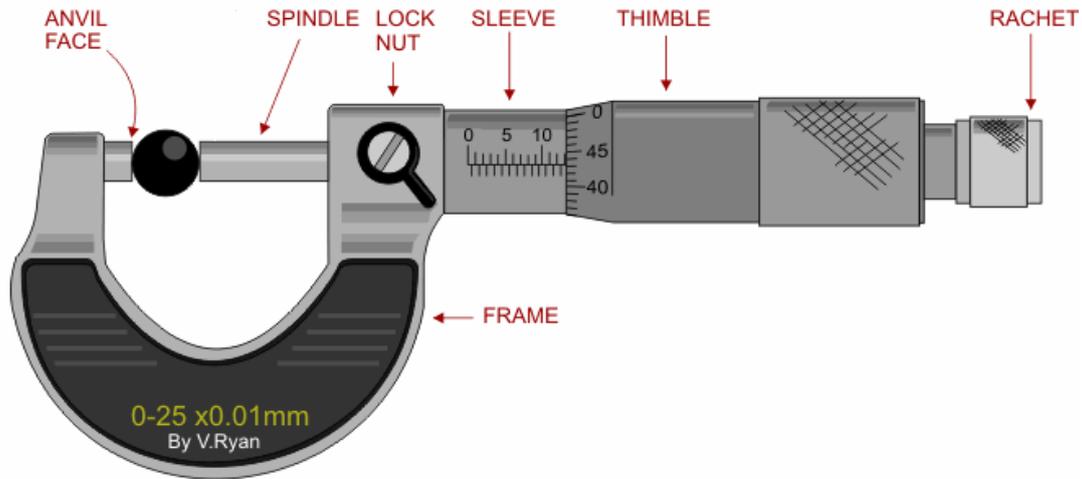


Figure 9: Parts of a screw gauge

The parts of the screw gauge include:

1. Frame: The C-shaped body that holds the anvil and barrel in constant relation to each other.
2. Anvil: The shiny part that the spindle moves toward, and that the sample rests against.
3. Spindle: The shiny cylindrical component that the thimble causes to move toward the anvil.
4. Lock nut: The knurled component (or lever) that one can tighten to hold the spindle stationary, such as when momentarily holding a measurement.
5. Sleeve: The stationary round component with the linear scale on it, sometimes with vernier markings. In some instruments the scale is marked on a tight-fitting but movable cylindrical sleeve fitting over the internal fixed barrel.
6. Thimble: The component that one's thumb turns. Graduated markings.
7. Ratchet: Device on end of handle that limits applied pressure by slipping at a calibrated torque.

## Least count of the instrument

The pitch of the screw is the distance moved by the spindle per revolution. It can be represented as

$$\text{Pitch of the screw} = \frac{\text{Distance moved by the screw}}{\text{No. of full rotations given}} \quad (2)$$

The least count (LC) is the distance moved by the tip of the screw, when the screw is turned through 1 division of the head scale. It can be calculated using the formula

$$\text{Least count (LC)} = \frac{\text{Pitch}}{\text{Total number of divisions on the circular scale}} \quad (3)$$

<sup>3</sup>Image source: <https://scienceportfolio1p1.wikispaces.com/Term+1>

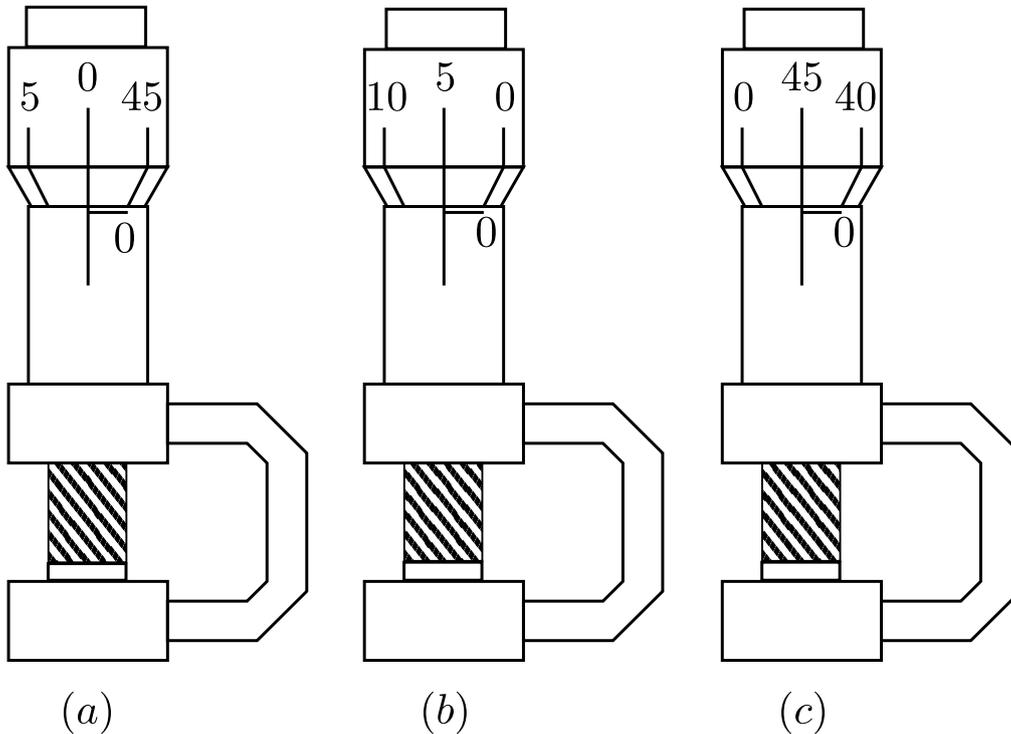


Figure 10: Screw gauge (a) without any zero error (b) with positive zero error (c) with negative zero error.

### Measurement with the instrument

1. Insert the object in between the anvil and the spindle and rotate the ratchet until the object is gently gripped between the anvil and the stud. Stop as soon as a click sound is heard.
2. Note down the circular (CSR) and the linear/main scale (MSR) readings.
3. The length of the object is then given by

$$\text{Length} = \text{MSR} + \text{CSR} \times \text{LC} \quad (4)$$

4. Repeat steps 1-3 three times and note the average reading.

### Zero error

When the anvil and the spindle touch without any object between them, the zero of the circular scale should coincide with the main scale line as shown in Fig. 10(a)

### Positive zero error

However, if the circular scale zero is above the linear scale, the instrument has **positive zero error** as shown in Fig. 10 (b) and the **correction is negative**.

### Negative zero error

When the circular scale is below the linear scale, the instrument has **negative zero error** as shown in Fig. 10(c) and the **correction is positive**.

# Experiment 1

## Introduction to Error Analysis and Graph Drawing

### 1.1 Finding $\tau$ and initial voltage across capacitor

You are given below the voltage decay as function of time across a capacitor in a  $RC$  circuit.

1. Obtain the value of characteristic decay time constant by plotting the data in a semi-logarithmic paper.
2. Obtain the initial value of the voltage across the capacitor.

Time (s)	Voltage (V)
6.2	5.53
8.7	4.89
10.0	4.58
12.5	4.04
16.3	3.35
18.4	3.05
22.5	2.45
25.0	2.16
28.5	1.85
32.9	1.44
38.8	1.09
42.0	0.92
47.8	0.70
52.0	0.56
55.4	0.47
62.5	0.33
67.2	0.26

Table 1.1: Data of voltage decay in a capacitor as a function of time.

The equation governing the relation between voltage and time for the capacitor is as given below.

$$v = v_0 e^{-t/\tau} \quad (1.1)$$

$$\log v = \log v_0 - \log e^{t/\tau} \quad (1.2)$$

$$\log v = \log v_0 - \frac{t}{\tau} \log e \quad (1.3)$$

From  $\log_{10} v$  vs  $t$  plot, the value of  $\tau$  can be obtained.

## 1.2 Resonant Rings

In an experiment, paper rings of different diameter are mounted on a vibrating table to study their resonant frequencies. Depending on the diameter, the rings show resonant vibration for different frequencies of the vibrating table. The data from this experiment is given in Table 1.2. Use the formula  $F = CD^n$ .

Diameter of the ring ( <i>cm</i> )	3.4	4.6	6.4	8.7	10.9	13.2
Resonant frequency ( <i>Hz</i> )	63.48	30.77	13.38	6.24	3.58	2.19

Table 1.2: Data of resonant frequencies as a function of diameter of the rings

1. Plot resonant frequency vs diameter of the ring in a log-log graph to obtain the mathematical relationship between the two variables.
2. From your graph predict the resonant frequency for a ring of diameter 16 *cm*.

## 1.3 Mass Spring System

A spring (of mass 50 *g*) is suspended vertically. It is pulled slightly downward and time for 20 free oscillations is observed. Repeat the observations for three times. Calculate the average time period of this spring system. Now, using the equation, given below, calculate the force constant  $k$  of the spring, to two decimal places.

$$T = 2\pi \sqrt{\frac{m_o + (m_s/3)}{k}} \quad (1.4)$$

where  $m_o$  is mass of weight hanged and  $m_s$  is the mass of the spring.

### Observation table

Sl.	$T_{20}$ (sec)	Mean $T_{20}$ (sec)	$T$ (sec)	$k$ (N/m)
1				
2				

Table 1.3: Table to calculate the spring constant of a spring.

From the Eq. (1.4) the error in calculating  $k$  is obtained as follows. If  $m_0 = 0$ , then squaring Eq. (1.4) and re-arranging the terms we have,

$$k = \frac{4\pi^2}{3} \left( \frac{m_s}{T^2} \right)$$

Taking log on both sides,

$$\log k = \log \left( \frac{4\pi^2}{3} \right) + \log m_s - 2 \log T$$

Taking derivative on both sides,

$$\frac{\Delta k}{k} = \frac{\Delta m_s}{m_s} + 2 \left( \frac{\Delta T}{T} \right) \quad (1.5)$$

where we have changed the sign of in front of  $\Delta T$  to calculate the maximum error.

## 1.4 Resistivity of a of nichrome wire

A homogeneous nichrome wire along with a digital multimeter and a screw gauge is given to you.

1. Measure the resistance of the nichrome wire for three different lengths of the wire.
2. Use the screw gauge to determine the diameter of the wire.
3. Determine resistivity of the nichrome wire from your measurements using the formula

$$\rho = \frac{R\pi d^2/4}{L}, \quad (1.6)$$

where,  $R$  = resistance of the nichrome wire,  
 $d$  = diameter of the nichrome wire,  
 $L$  = length of the nichrome wire. (1.7)

4. From Eq. (1.6) one can obtain  $\frac{\Delta \rho}{\rho} = \frac{\Delta R}{R} + 2\frac{\Delta d}{d} + \frac{\Delta L}{L}$  and finally obtain  $\Delta \rho$  for this experiment.

### Observation table

Total number of circular scale (CS) divisions of the screw gauge = .....

One main scale division (MSD) = ..... cm

Number of rotations required on the CS to cover 1 MSD = .....

Zero error on the CS = .....

Least count (l.c) of the screw gauge

$$l.c = \frac{\text{One main scale division (1 MSD)}}{\text{No. of rotations on the CS} \times \text{Total number of CS divisions}} \text{ cm} \quad (1.8)$$

Sl. No.	MSR ( $a$ )	CSR ( $b$ )	Total ( $a + b \times l.c$ ) (cm)
1			
2			

Table 1.4: Table to calculate the diameter of the nichrome wire

Sl.	$L$ (cm)	Resistance ( $\Omega$ )	$\rho$ ( $\Omega$ m)
1			
2			

Table 1.5: Table to calculate the resistivity of the wire

## 1.5 To measure the electrical resistance of a given material

The resistance of the wire is measured with the help of a Wheatstone bridge up to the accuracy of three significant figures. By using the relation.

$$\frac{P}{Q} = \frac{R}{S} \quad (1.9)$$

where  $S$  is a variable resistor and  $R$  is an unknown resistor. If the ratio of the two known resistances  $P/Q$  is equal to the ratio of the two unknown resistances  $R/S$ , then the voltage difference between the points  $A$  and  $B$  will be zero and no current would flow through the galvanometer  $G$ . In case there is a voltage difference between points  $A$  and  $B$ , direction of the current in the galvanometer indicates the direction of flow of current through the bridge. In this manner an unknown resistance  $R$  can be calculated to an accuracy of high degree. Fig. 1.2 shows the experimental setup of a wheatstone bridge.

### Observation table(No. of readings: 2 with different lengths)

Sl. No.	1000 ( $\Omega$ ) ( $a$ )	100 ( $\Omega$ ) ( $b$ )	10 ( $\Omega$ ) ( $c$ )	1 ( $\Omega$ ) ( $d$ )	Multiplier ( $m$ )	$R$ ( $\Omega$ )
1					1	
2					0.1	
3					0.01	
4					0.001	

where  $R = m \times (a \times 1000 + b \times 100 + c \times 10 + d \times 1) \Omega$ . The value obtained on the bottom right most cell in the above table is your final answer to an accuracy of 0.001 $\Omega$ . The final answer is NOT the average of all the  $R$  values. Why?

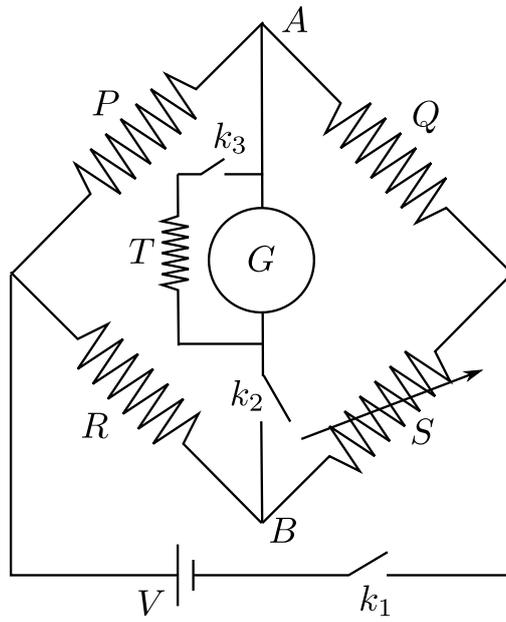


Figure 1.1: A wheatstone bridge.



Figure 1.2: A wheatstone bridge setup.

## Experiment 2

# Acceleration due to gravity by bar pendulum

### Purpose

To determine the value of acceleration due to gravity using angular oscillations of a long bar.

### Apparatus

Stop watch, long bar, meter scale, knife edge.

### Theory

The purpose of this experiment is to use angular oscillations of rigid body in the form of a long bar for determining the acceleration due to gravity. The particular form of the body is chosen for the sake of simplicity in performing the experiment. The bar is hung from a knife-edge through one of the many holes along the length. It is free to oscillate about the knife-edge as axis. Any displacement  $\theta$ , from the vertical position of equilibrium would give rise to an oscillatory motion just as in the case of a simple pendulum. The difference is that since this is rotating rigid body here we consider the torque of the gravitational force giving rise to the angular acceleration.

The restoring torque  $\tau$  for an angular displacement  $\theta$  is

$$\tau = -Mgd \sin \theta \quad (2.1)$$

where  $M$  is the mass of the compound pendulum and  $d$  the distance between the point of suspension  $O$  and the centre of mass of the bar  $C$ .

Since  $\tau$  is proportional to  $\sin \theta$ , rather than  $\theta$ , the condition for simple angular harmonic motion does not, in general, hold here. For small angular displacements, however, the relation  $\sin \theta \approx \theta$  is a good approximation, so that for small amplitudes in turn for small values of  $\theta$ .

$$\tau = -Mgd\theta = I \frac{d^2\theta}{dt^2} \quad (2.2)$$

where  $I$  is the moment of inertia of the bar about the point of suspension  $O$ . The solution of the above equation is given by

$$\theta(t) = A \sin(\omega t + \phi) \quad (2.3)$$

$$\text{where, } \omega = \frac{2\pi}{T} = \sqrt{\frac{Mgd}{I}} \quad (2.4)$$

is the angular velocity of the compound pendulum. Thus, the period of oscillation is given by

$$T = 2\pi\sqrt{\frac{I}{Mgd}} \quad (2.5)$$

Due to the parallel axis theorem we have

$$I = I_0 + Md^2, \quad (2.6)$$

where,  $I_0$  is the moment of inertia of the pendulum about its center of gravity (C.G).

Inserting Eq. (2.6) in Eq. (2.5), we get the complete  $d$  dependence of the time period  $T$  as

$$T = 2\pi\sqrt{\frac{I_0 + Md^2}{Mgd}} \quad (2.7)$$

Since  $I_0$  can be expressed as  $Mk^2$ , where  $k$  is the radius of gyration, Eq. (2.7) can be rewritten as

$$T = 2\pi\sqrt{\frac{Mk^2 + Md^2}{Mgd}} = 2\pi\sqrt{\frac{k^2 + d^2}{gd}}. \quad (2.8)$$

A simple pendulum consists of a mass  $m$  hanging at the end of a string of length  $L$ . The time period of a simple pendulum is given by

$$T = 2\pi\sqrt{L/g}. \quad (2.9)$$

So, the time period of a simple pendulum equals the time period of a compound pendulum when

$$L = \frac{d^2 + k^2}{d} \quad (2.10)$$

Re-arranging the above equation

$$d^2 - Ld + k^2 = 0 \quad (2.11)$$

gives us a quadratic equation in  $d$ . If  $d_1$  and  $d_2$  are the two solutions of the above equation, then we find

$$d_1 + d_2 = L \quad (2.12)$$

$$d_1d_2 = k^2 \quad (2.13)$$

Since both  $d_1$  and  $d_2$  are positive, we conclude that there are two points of suspension on one side of the C.G. of the compound pendulum where the time periods are equal. Similarly, there are two points of suspension on the other side of the C.G. where the time periods are same. Thus, for a compound pendulum, there are four points of suspension, two on either side of the C.G. where the time periods are equal. The simple equivalent length  $L$  is sum of two of these points of suspension located asymmetrically on two sides of the C.G.

To facilitate further analysis it is useful to square Eq. (2.7) to get

$$T^2 = 4\pi^2 \left( \frac{I_0 + Md^2}{Mgd} \right) \quad (2.14)$$

In order to gain insight in the dependence of  $T$  on  $d$  let us first look at the dependence for (i) small  $d$  and (ii) large  $d$ . For small  $d$  (specifically for  $Md^2 \ll I_0$ ) we have

$$T^2 \sim 4\pi^2 \frac{I_0}{Mgd} \quad (2.15)$$

$$T \sim \frac{1}{\sqrt{d}}. \quad (2.16)$$

Thus  $T$  decreases as  $d$  increases. In the opposite limit i.e. for large  $d$  (specifically for  $Md^2 \gg I_0$ ) we have

$$T^2 \sim 4\pi^2 \frac{Md^2}{Mgd} \quad (2.17)$$

$$T \sim \sqrt{d} \quad (2.18)$$

Thus  $T$  increases as  $d$  increases in this case. Physically the origins of  $d^2$  in the numerator is coming from the expression for the moment of inertia  $I \sim d^2$ .

It is then just a question of which effect dominates for a given values of  $d$ . To understand this better (or more quantitatively) let us look at the turning point. The minimum of the expression for  $T^2$  as a function of  $d$  can be determined by taking the derivative of  $T^2$  with respect to  $d$  and setting it equal to zero (and ensuring the sign of the second derivative term corresponds to a minimum). Following this procedure gives

$$d = \sqrt{\frac{I_0}{M}} \quad (2.19)$$

Eq. (2.19) can be written as  $I_0 = Md^2$ . This relation is satisfied at the minimum or at the turning point. Using this in Eq. (2.7) we find that the turning point occurs when the magnitude of the two terms of the numerator are equal. For  $Md^2 \ll I_0$  the  $I_0$  term dominates in the numerator and  $d$  dependence is given by the denominator. In the region  $Md^2 \gg I_0$  the  $Md^2$  term dominates in the numerator and so the  $d$  dependence is dominated by the numerator.

## History of the experiment

Galileo was the first person to show that at any given place, all bodies fall freely when dropped, with the same (uniform) acceleration, if the resistance due to air is negligible. The gravitational attraction of a body towards the center of the earth results in the same acceleration for all bodies at a particular location, irrespective of their mass, shape or material, and this acceleration is called the acceleration due to gravity,  $g$ . The value of  $g$  varies from place to place, being greatest at the poles and the least at the equator. However, direct measurement of the acceleration due to gravity is very difficult.

Therefore, the acceleration due to gravity is often determined by indirect methods, for example, using a simple pendulum or a compound pendulum. If we determine  $g$  using a simple pendulum, the result is not very accurate because an ideal simple pendulum cannot be realized under laboratory conditions. Hence, a compound pendulum is used to determine the acceleration due to gravity in the laboratory.

## Procedure

- Balance the bar on sharp wedge and mark the position of its center of gravity (C.G.).
- Ensure that the frame on which movable knife edge / pivot is to be rested is horizontal.

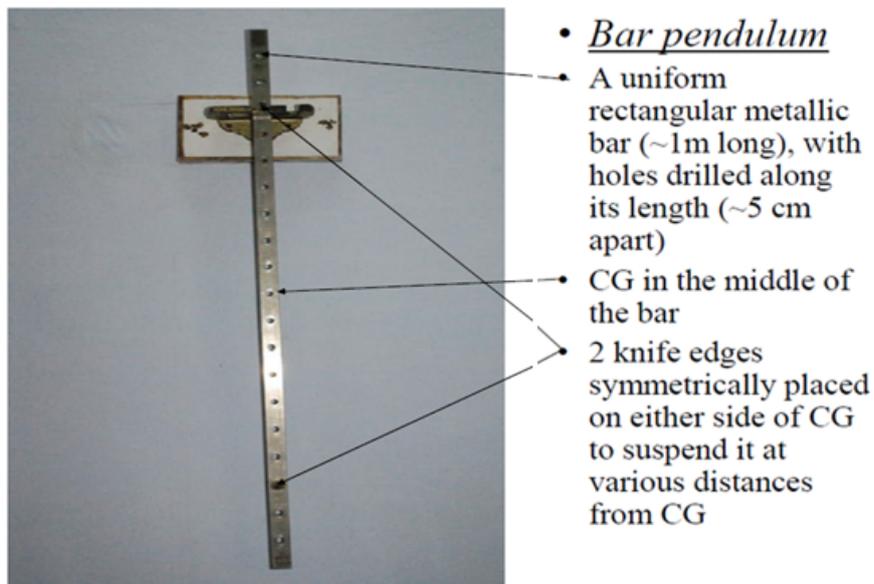


Figure 2.1: Image of a bar pendulum

Sl.	$d$	No. of oscillations			Mean $T_{10}$	$T$
		1	2	3		
–	(cm)	(sec)	(sec)	(sec)	(sec)	(sec)
⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 2.1: Table to measure acceleration due to gravity via a compound pendulum.

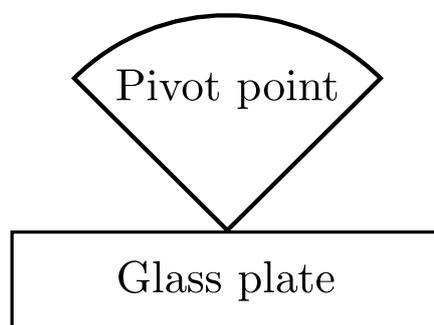


Figure 2.2: Pivot or knife edge of the bar pendulum

- Suspend the pendulum in the first hole. The knife edge or pivot should be placed on the glass plate as shown in Fig. 2.2.

- The distance  $d$  is the distance between point of suspension (bottom of the hole) and the C.G.
- Start the oscillation of the pendulum.
- Use the stop watch to measure the time for 10 oscillations. The time should be measured after the pendulum has had a few oscillations and the oscillations have become regular.
- Repeat the process by suspending the pendulum in the consecutive holes.
- Draw a graph by taking distance along  $X$ -axis and time period along  $Y$ -axis as shown in Fig. 2.3. Shift the axes to draw a full page graph.

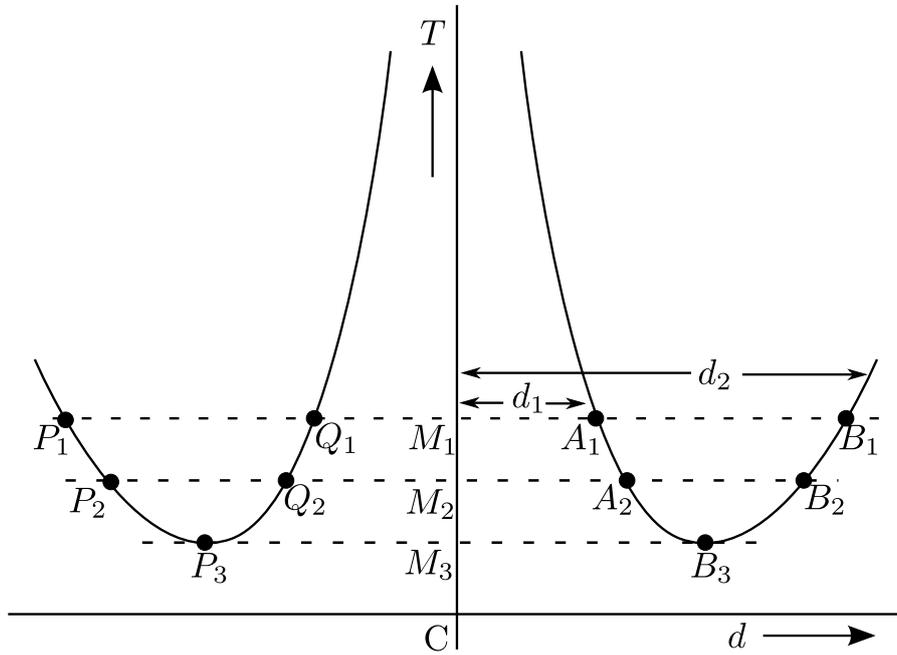


Figure 2.3: Plot of time vs distance from center of gravity of bar

## Calculation

1. With the help of the graph, distance  $d_1$  and  $d_2$  can be measured from which the value of  $g$  can be calculated by using formulas

$$d_1 + d_2 = L \quad (2.20)$$

$$g = \frac{4\pi^2 L}{T^2} \quad (2.21)$$

where  $d_1$  and  $d_2$  the distances  $M_1A_1$ ,  $M_1B_1$  respectively and  $T$  is the time  $CM_1$  as shown in Fig. 2.3. As there are two branches one could take the mean of  $Q_1M_1$  and  $M_1A_1$  for the distance  $d_1$  and mean of  $P_1M_1$  and  $M_1B_1$  for the distance  $d_2$  for substitution in this formula.

2. Choose another line  $P_2B_2$  and find  $g_2$  using Eqns. (2.20) and (2.21), where  $d_1$  is the mean of  $Q_2M_2$  and  $M_2A_2$ ,  $d_2$  is the mean of  $P_2M_2$  and  $M_2B_2$  and  $T = CM_2$ .

- At the minima, ensure that  $P_3M_3$  is equal to  $M_3B_3$ . Then calculate  $g_3$  via the formula

$$g = 4\pi^2 \frac{P_3B_3}{CM_3^2} \quad (2.22)$$

- Find the average value of  $g$ .

## Theoretical error

Acceleration due to gravity ( $g$ ) is given by the formula

$$g = \frac{4\pi^2 L}{T^2} \quad (2.23)$$

Taking log and differentiating

$$\frac{\partial g}{g} = \frac{\partial L}{L} + 2 \frac{\partial T}{T} \quad (2.24)$$

Thus, maximum possible error = .....%.

## Results

- The standard value of  $g = \dots\dots\dots m/sec^2$ .
- Percentage error = .....%.

## Precaution

- The Knife edge is made horizontal. If it is not perfectly horizontal the bar may be twisted while swinging.
- The motion of a bar should be strictly in a vertical plane.
- The amplitude of the swing should be small.
- The time period of oscillations should be determined by measuring time by large number of oscillations with an accurate stop watch.
- All distances should be measured and plotted from one end of the rod.

# Experiment 3

## $e/m$ of electron by Thomson Method

### Purpose

Determining the value of specific charge  $e/m$  of an electron by Thomson Method

### Apparatus

Deflection magnetometer, two bar magnets, cathode ray oscilloscope, stand arrangement.

### Theory

In this method, a cathode ray tube is used in which the cathode emits electrons and the anode accelerates them and passes them through a small hole, to another anode which concentrates them into a fine beam. Then they are passed between two parallel plates, which can deflect the beam in a vertical plane by an electric field  $E$  applied between both the plates. The beam of electrons can also be deflected in the same plane by applying a magnetic field  $B$  perpendicular to the plane of plates. This narrowed collimated beam of accelerated electrons then strikes the fluorescent screen to produce a glowing spot. Three terms arise as follows:

1. If an electric field  $E$  is applied by a potential difference of  $V$  volts between the plates, the electrons experience a force  $F_e$  in a direction perpendicular to the direction of motion of the beam.

$$F_e = Ee \quad (3.1)$$

2. If  $B$  is the uniform magnetic field applied in an horizontal direction perpendicular to the direction of the electron beam, the magnetic force  $F_{mag}$  experienced by the electrons is

$$F_{mag} = e|\vec{v} \times \vec{B}| = Bev \sin 90^\circ = Bev \quad (3.2)$$

where  $e$  is the electron charge and  $v$  is the velocity of the electrons. This force  $F_{mag}$  acts perpendicular to the direction of  $B$  as well as in the original direction of electron motion (in accordance with Fleming's left rule for electric motor). The speed of electrons remains unchanged, but their path becomes circular, providing the centripetal force

$$F_{mag} = Bev = mv^2/r \quad (3.3)$$

where  $m$  is the mass of an electron and  $r$  is the radius of the circular path. Thus

$$e/m = v/Br \quad (3.4)$$

3. If an electric field  $E$  is applied to deflect the beam in  $OO'$  direction (see Fig. 3.1), then a magnetic field  $B$  is applied to bring beam back to  $O$ . It means that the force of the electrostatic field is equal and opposite to applied magnetic field, so  $F_e = F_{mag}$ , and two forces null each other to bring the beam back to its original position. Thus

$$\begin{aligned} Ee &= Bev \\ \text{or, } v &= E/B \end{aligned} \quad (3.5)$$

Substituting value of  $v$  from Eq.3.5 into Eq. 3.4,

$$\frac{e}{m} = \frac{E}{B^2 r} \quad (3.6)$$

According to Fig.3.1, the original electron beam proceeds on the straight path  $G, M, O$  and impresses upon the screen at a point  $O$ . In the presence of magnetic field, the beam travels along a circular arc  $G, D$  whose radius is  $r$ . Beyond point  $D$ , the beam leaves the magnetic field and proceeds straight in the direction along the tangent  $KDO'$  (drawn on the circular arc at point  $D$ ).  $GN$  is normal to  $GKO$  and  $MDN$  is normal to  $KDO'$ . Let these normals meet at point  $N$ . Then  $GN = ND = r =$  the radius of the circular arc. Let the angles  $GND = OKO' = \theta$ . Then in the triangle  $KOO'$ ,

$$\tan \theta = OO'/KO \quad (3.7)$$

and if the angle  $\theta$  is small enough,

$$\theta = \tan \theta = y/L \quad (3.8)$$

where  $L$  is distance of the screen from the mid point of the magnetic field region (generally mid point of electric field too). Again,

$$\theta = \tan \theta = \text{arc } GD/r = GM/r, \quad (3.9)$$

since  $GD$  is nearly equal to  $GM$ , or

$$\theta = l/r \quad (3.10)$$

where  $l$  is the length of the region of magnetic field, equal to the region of electric field. By comparing both values of  $\theta$

$$l/r = y/L. \quad (3.11)$$

So

$$r = lL/y \quad (3.12)$$

Substituting the value of  $r$  into Eq.3.6,

$$\frac{e}{m} = \frac{Ey}{B^2 lL} \quad (3.13)$$

If a potential difference of  $V$  volts is applied between the plates  $P-P$ , and  $d$  is the gap between both plates, then the electric field is given by  $E = V/d$ . Therefore,

$$\frac{e}{m} = \frac{Vy}{B^2 lLd} \quad (3.14)$$

where  $y$  is the distance between spot positions displayed on the screen of CRT in centimeters,  $l$  is the length of the deflection plates,  $L$  is the distance between screen and plates,  $d$  is the distance between plates,  $V$  is applied DC voltage across plates and  $B$  is magnetic field strength determined by  $B = H \tan \theta$ , where  $H$  is the horizontal component of earth's magnetic field at that place.

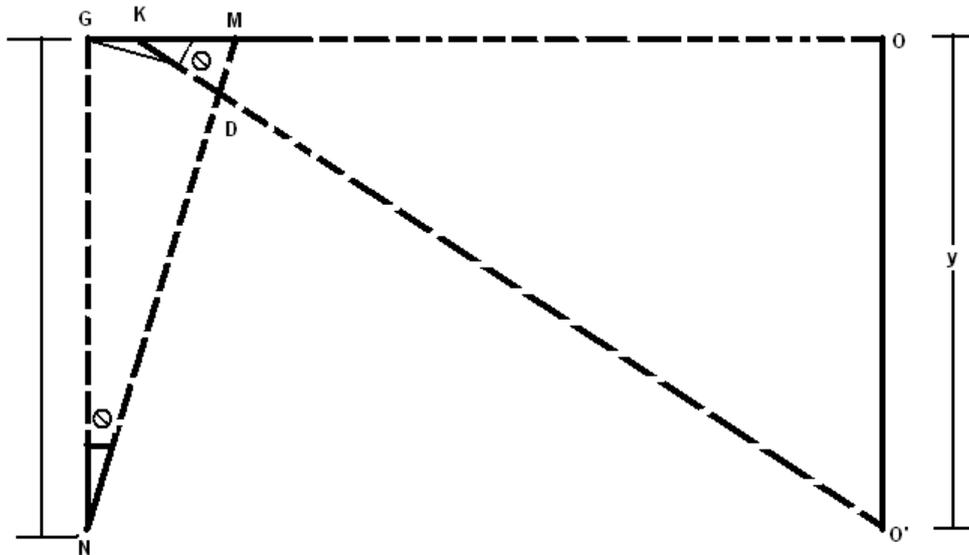


Figure 3.1: Electron beam diagram in magnetic field

## Procedure

1. Using compass needle, find and note North-South and East-West directions. Place CRT in between the stand in such a way that its screen is faced towards North and both arms stand to East-West direction.
2. Adjust the Intensity and Focus potentiometer to its mid position.
3. Connect the CRT to octal socket of instrument (socket provided upon the panel). Care should be taken while inserting CRT plug.
4. Keep instrument to south direction far from CRT.
5. Select polarity selector switch at '0' position.
6. Set the deflection voltage potentiometer at anti-clockwise direction.
7. Switch on the power supply and wait for some time (3-5 minutes) to warm up the CRT. A bright spot appears on the screen.
8. Adjust intensity and focus controls to obtain a sharp spot.
9. Bring the spot at the middle position of the CRT with the help of X-plate deflection voltage pot given at the back-side of the instrument.
10. Set polarity selector to '+' position, and adjust deflection voltage to deflect the spot 1 cm away towards upward. Note the deflection voltage from the meter as  $V_1$  and spot deflection as  $y$ .
11. Now place the bar magnets (on the stand arm) to both sides of CRT such that their opposite poles face each other.
12. Adjust position of magnets to get spot back downward to original position.
13. Note the distances of bar magnet (poles facing the screen) as  $r_1$  and  $r_2$  from the scale.
14. Now remove magnets from the arms of stand.

15. Select ‘-’ position of polarity switch. Apply DC voltage to deflect the spot 1 cm away in downward direction. Note deflection voltage from display as  $V_2$  and deflection as  $y$ .
16. Place bar magnets again and adjust the position of magnets to bring spot back to original position. Note the distance of the magnets (poles facing the screen) as  $r'_1$  and  $r'_2$ .
17. Remove CRT and magnets. Place magnetometer arrangement in between the stand such that its centre lies on the center of the stand arm.  
Note: Position of stand should not be disturbed.
18. Rotate magnetometer and adjust the needle to read  $0^\circ - 0^\circ$ .
19. Now place magnets at a distance equal to  $r_1$  and  $r_2$  as previous polarity adjusted. The pointer deflects along the scale. Note the deflections as  $\theta_1$  and  $\theta_2$ .
20. Repeat similar procedure placing magnets at  $r'_1$  and  $r'_2$  distances. Note the deflection of compass needle as  $\theta_3$  and  $\theta_4$ .
21. Now we know that magnetic field

$$B = H \tan \theta, \quad (3.15)$$

$$\text{where, } \theta = \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4}{4} \quad (3.16)$$

$$\text{and, } H = 0.37 \times 10^{-4} \text{ Tesla} \quad (3.17)$$

22. Calculate  $e/m$  using the following formula

$$\frac{e}{m} = \frac{Vy}{B^2 l L d} \quad (3.18)$$

where,  $d =$  distance between plates = 1.4 cm

$l =$  length of plates = 3.23 cm

$L =$  distance between screen and plates = 14.5 cm

$V =$  deflection voltage =  $(V_1 + V_2)/2$

$y =$  deflection in cm = 1 cm

23. Take more readings by repeating the experiment and deflecting spot to other distances.
24. Calculate the percentage error as

$$(\text{Standard value} - \text{Calculated value}) / \text{Standard value} \times 100 \quad (3.19)$$

Note: While performing the experiment, keep other electronics equipment away from the  $e/m$  setup.

### Precautions and sources of error

- The cathode ray tube should be handled carefully. There should not be any magnetic substance nearby the place of experiment.

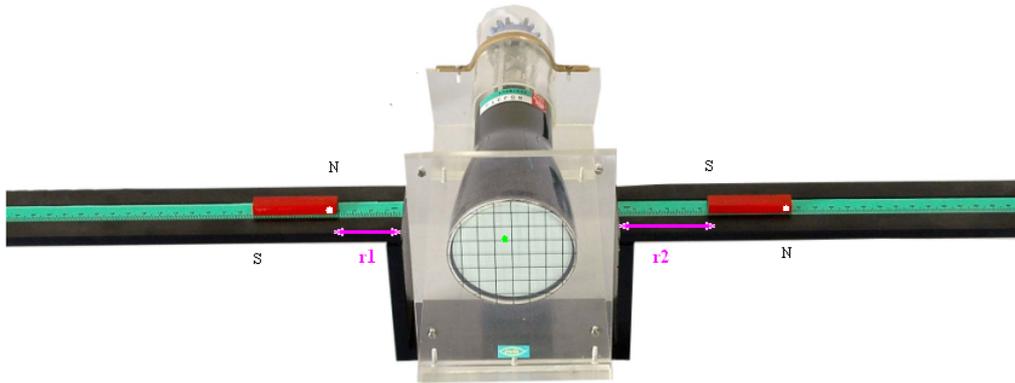


Figure 3.2: Set-up of Thomson Method experiment



Figure 3.3: Cathode ray tube used in Thomson Method

- Axis of magnets and axis of tube should lie perpendicular to each other in same horizontal plane. To correct it, loosen the neck clamp of CRT and rotate CRT so the spot deflects right up/down with deflection voltage.
- When magnets are placed upon the arms, it is better to move stand slightly back and forth to obtain maximum magnetic field at deflecting plates. It should be done before bringing spot back to original position.
- Rotate magnet(s) on their axes if spot does not come back to its original position.
- When direction of spot is reversed the direction of magnets should also be reversed.
- The magnets should move tight to the scale in closest possible distances.
- The electric field between plates cannot be uniform due to short distance between them.
- The given constants are generally taken from data; there may be slight variations to produce error.

## Results

Standard Value of  $e/m$ : ..... C/Kg

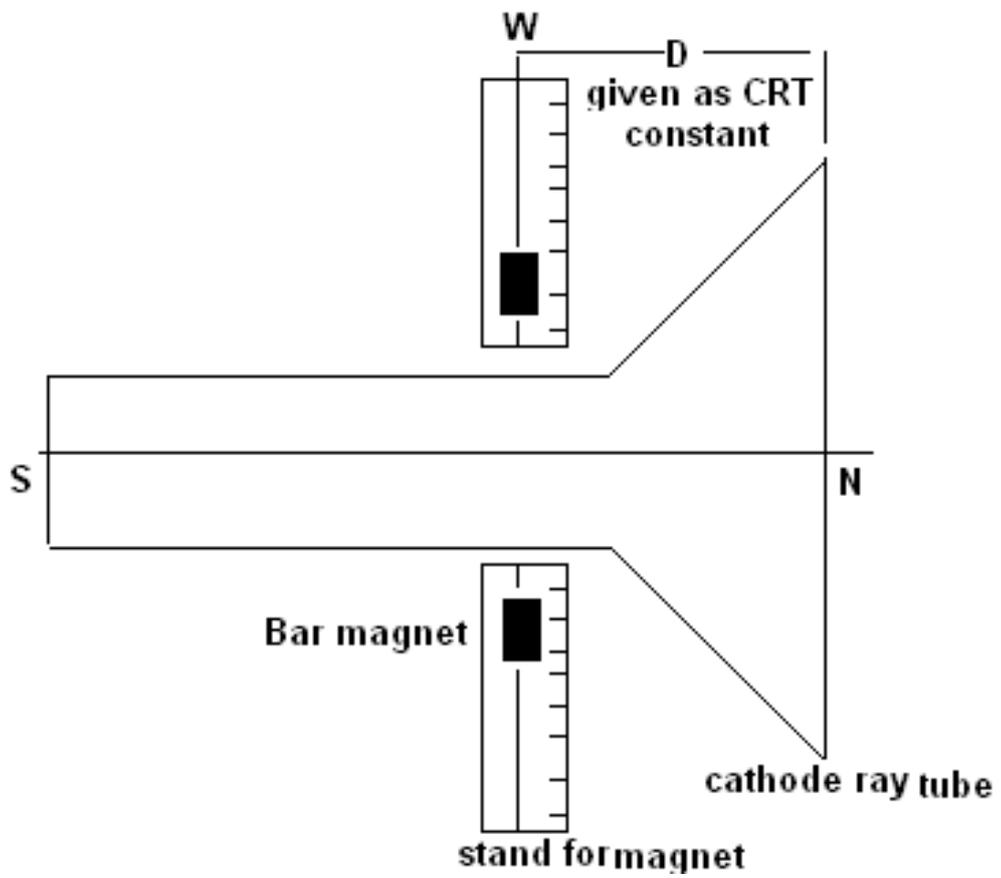


Figure 3.4: Way to place cathode ray tube

## Experiment 4

# Measurement of band gap of semiconductor

### Purpose

- Measurement of resistivity of a semiconductor at room temperature
- Measurement of variation of resistivity with temperature.
- Evaluation of band gap of the given semiconductor from the plotting of acquired data.
- Understanding of the concept of four probe method.

### Apparatus

Four probe experimental setup.

### Theory

#### Semiconductor

Semiconductor is a very important class of materials because of wide applications in this modern world. The following are the properties which gives a rough description of a semiconductor.

1. The electrical conductivity of a semiconductor is generally intermediate in magnitude between that of a conductor and an insulator. That means conductivity is roughly in the range of  $10^3$  to  $10^{-8}$  siemens per centimeter.
2. The electrical conductivity of a semiconductor varies widely with doping concentration, temperature and carrier injection.
3. Semiconductors have two types of charge carriers, electrons and holes.
4. Unlike metals, the number of charge carriers in semiconductors largely varies with temperature.
5. Generally, in case of semiconductor, increase of temperature enhances conductivity while in case of metals increase of temperature reduces conductivity.
6. The semiconductor can be best understood in the light of energy band model of solid.

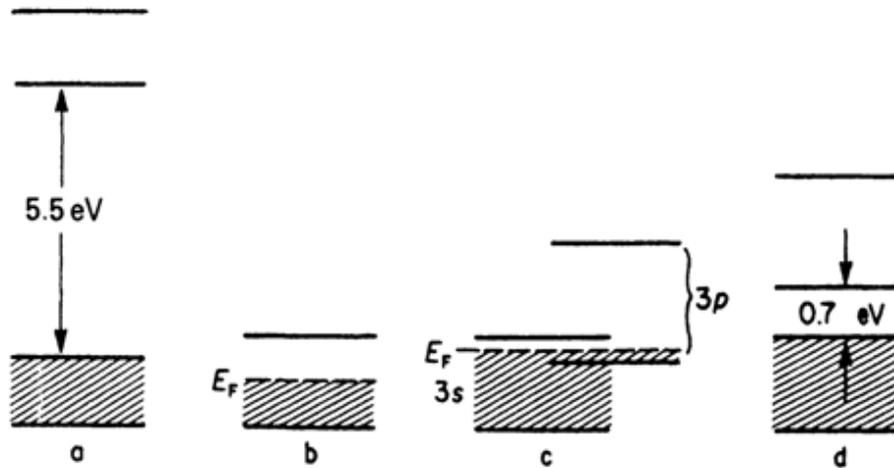


Figure 4.1: Band gaps shown for (a) Insulator (b) Alkali Metal (c) Other Metal (d) Semiconductor

### Energy band structure of solid

Atom has discrete energy levels. When atoms are arranged in a periodic arrangement in a solid the relatively outer shell electrons no longer remain in a specific discrete energy level. Rather they form a continuous energy level, called energy band. In case of semiconductor and insulator, at temperature  $0K$  all the energy levels up to a certain energy band, called valence band, are completely filled with electrons, while next upper band (called conduction band) remains completely empty. The gap between bottom of the conduction band and top of the valence band is called *fundamental energy band gap* ( $E_g$ ), which is a forbidden gap for electronic energy states. In case of metals, valence band is either partially occupied by electrons or valence band has an overlap with conduction band, as shown in Fig. 4.1(b and c).

In case of semiconductor, the band gap ( $\sim 0 - 4eV$ ) is such that electrons can move from valence band to conduction band by absorbing thermal energy. When electron moves from valence band (VB) to conduction band (CB), it leaves behind a vacant state in valence band, called hole. When electric field is applied, movement of large number of electrons in the valence band can be visualized by the movement of hole as a positive charge particle. The  $E_g$  is a very important characteristic property of semiconductor which dictates its electrical, optical and optoelectrical properties. There are two main types of

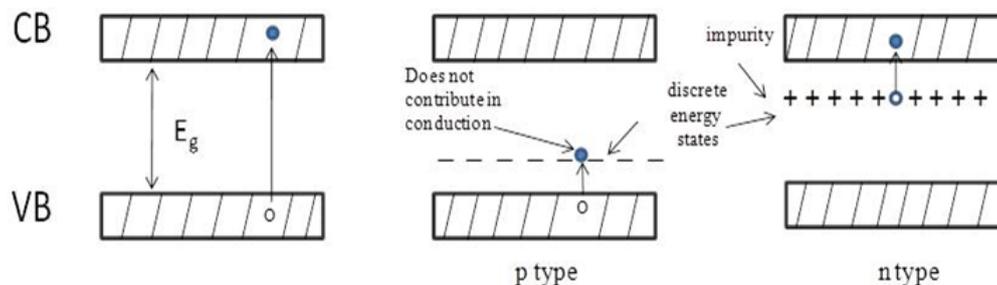


Figure 4.2: Energy band diagram of a semiconductor

semiconductor materials: intrinsic and extrinsic. Intrinsic semiconductor doesn't contain impurity. Extrinsic semiconductors are doped with impurities. These discrete impurity energy levels lie in the forbidden gap. In p-type semiconductor, acceptor impurity, which can accept an electron, lies close to the valence band and in n-type semiconductor, donor

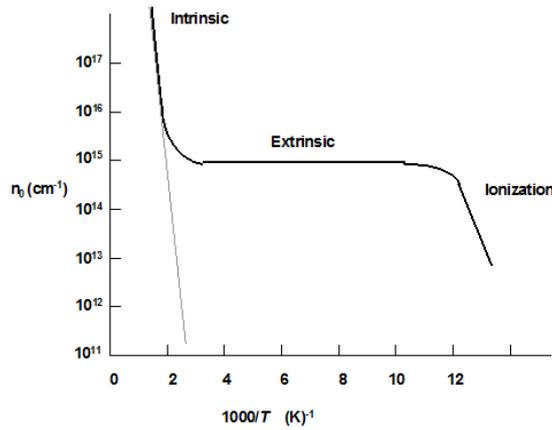


Figure 4.3: Temperature variation of carrier concentration

impurity, which can donate an electron lies close to conduction band.

### Temperature variation of carrier concentration

Fig. 4.3 shows the variation of carrier concentration (concentration of holes) in a p-type semiconductor with respect to  $1000/T$ , where  $T$  is the temperature. Initially as temperature increases from  $0K$  (i.e. ionization region), the discrete impurity vacant states starts getting filled up from valence band, which creates holes in valence band. Beyond a certain temperature all the impurity states will be filled up with electrons, which lead to the saturation region.

As temperature increases to further higher values, electrons, in the valence band, get sufficient energy to occupy empty states of conduction band (C.B). This region is called intrinsic region. The temperature above which the semiconductor behaves like intrinsic semiconductor is called “Intrinsic temperature”.

### Conductivity of a semiconductor

The conductivity of a semiconductor is given by

$$\sigma = e(\mu_n n + \mu_p p) \quad (4.1)$$

Where  $\mu_n$  and  $\mu_p$  refer to the mobilities of the electrons and holes, and  $n$  and  $p$  refer to the density of electrons and holes, respectively. The mobility is drift velocity per electric field applied across the material,  $\mu = V_d/E$ . Mobility of a charge carrier can get affected by different scattering processes.

### Effects of temperature on conductivity of a semiconductor

In the semiconductor, both mobility and carrier concentration are temperature dependent. So conductivity as a function of temperature can be expressed by

$$\sigma = e(\mu_n(T)n(T) + \mu_p(T)p(T)) \quad (4.2)$$

One interesting special case is when temperature is above intrinsic temperature where mobility is dominated by only lattice scattering ( $\propto T^{-3/2}$ ). That means in this temperature region mobility decreases with increase of temperature as  $T^{-3/2}$  due to increase of thermal vibration of atoms in a solid.

In the intrinsic region,  $n \approx p \approx n_i$ , where  $n_i$  is the intrinsic carrier concentration. The intrinsic carrier concentration is given by

$$n_i(T) = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} \exp \left( \frac{-E_g}{2kT} \right), \quad (4.3)$$

where,  $m_n^*$  and  $m_p^*$  are effective mass of electron and hole. Here the exponential temperature dependence dominates  $n_i(T)$ . The conductivity can easily be shown to vary with temperature as

$$\sigma \propto \exp \left( \frac{-E_g}{2kT} \right). \quad (4.4)$$

In this case, conductivity depends only on the semiconductor band gap and the temperature. In this temperature range, plot of  $\ln \sigma$  vs  $1000/T$  is a straight line. From the slope of the straight line, the band gap ( $E_g$ ) can be determined. The procedure of measurement of conductivity is given below.

### Four probe technique

Four probe technique is generally used for the measurement of resistivity of semiconductor sample. Before we introduce four probe technique, it is important to know two probe techniques by which you measured resistivity of a nicrome wire. In two probe technique, two probes (wires) are connected to a sample to supply constant current and measure voltage. In the case of nicrome wire (1<sup>st</sup> experiment), connections are made by pressing the multimeter probes on nichrome wire. The contact between metal to metal probe of multimeter does not create appreciable contact resistance. But in the case of semiconductor the metal – semiconductor contact gives rise to high contact resistance. If two probe configuration is followed for semiconductor sample, voltmeter measures the potential drop across the resistance of the sample as well as the contact resistance. This is shown in the Fig. 4.4(a).

The potential drop across high contact resistance can be avoided by using four probe technique. In the four probe configuration, two outer probes are used to supply current and two inner probes are used to measure potential difference. When a digital voltmeter with very high impedance is connected to the inner two probes, almost no current goes through the voltmeter. So, the potential drop it measures, is only the potential drop across the sample resistance. This is shown in the equivalent circuit diagram given in Fig. 4.4(b). From the measurement of current supplied and voltage drop across the sample, the resistance can be found out. Resistivity of a sample is given by  $\rho = cV/I$ , where  $c$  is a constant.

For the specific arrangement, where the probes are equispaced with the distance between two successive probes as  $a$ , and the thickness of the sample is  $h$ , the resistivity can be calculated by the following formulas.

**Case I:**  $h \gg a$ . In this case it is assumed that the four probes are far from the edge of the sample and the sample is placed on an insulating material to avoid leakage current. The resistivity in this case is given by

$$\rho = 2\pi a \frac{V}{I} \quad (4.5)$$

This is the setup used for our experiment.

**Case II:**  $h \ll a$ . In this case the resistivity is given by

$$\rho = \frac{\pi h}{\ln 2} \left( \frac{V}{I} \right) \quad (4.6)$$

Derivation for this is given at the end.

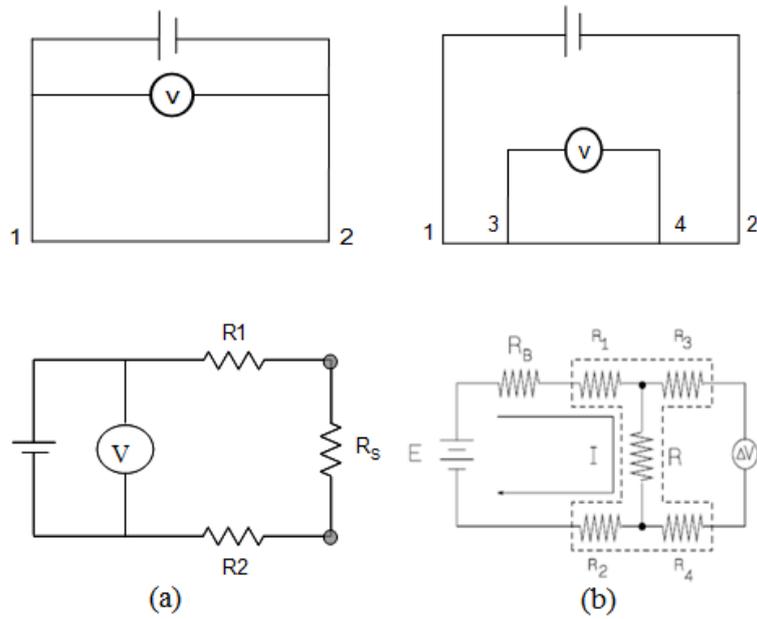


Figure 4.4: (a) Equivalent circuit for two probe measurement.  $R_1, R_2$  are the contact resistances (b) Equivalent circuit for four probe measurement.  $R_1, R_2$  and  $R_3, R_4$  are the contact resistances of current and voltage probes.

Once resistivity ( $\rho$ ) is determined, conductivity ( $\sigma$ ) can be calculated by taking reciprocal of it ( $\sigma = 1/\rho$ ).

### Advantages of using four probe method

- The key advantage of four-terminal sensing is that the separation of current and voltage electrodes eliminates the impedance contribution of the wiring and contact resistances.
- If the probes are separated by equal distance  $a$ , and  $a \ll h$  then resistivity can be found out without knowing the exact shape and size of the sample.

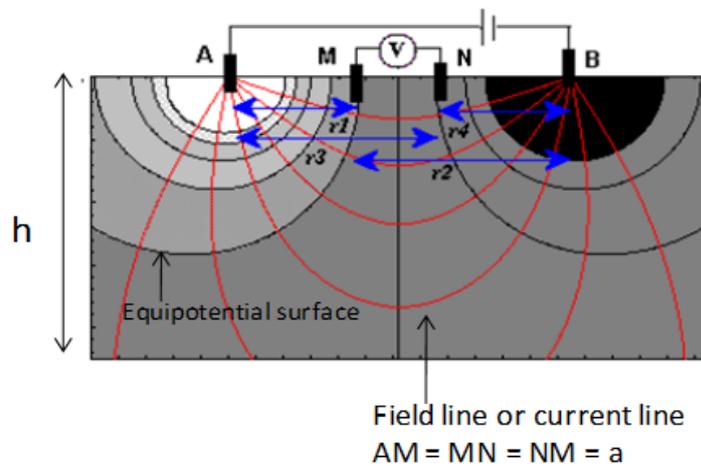


Figure 4.5: Pictorial representations of field lines generated by the applied potential.

## Description of the experimental set-up

**Probes arrangement** It has four individually spring loaded probes. The probes are collinear and equally spaced. The probes are mounted in a teflon bush, which ensure a good electrical insulation between the probes. A teflon spacer near the tips is also provided to keep the probes at equal distance. The whole arrangement is mounted on a suitable stand and leads are provided for the voltage measurement.

**Sample** Germanium crystal in the form of a chip.

**Oven** It is a small oven for the variation of temperature of the crystal from the room temperature to about  $200^{\circ}C$  (max).

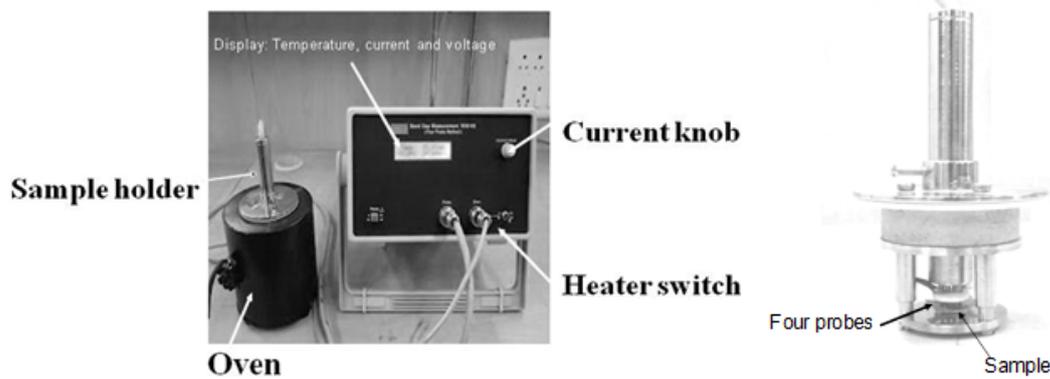


Figure 4.6: Four probe experimental setup.

## Procedure

- Switch ON the band gap setup.
- Supply current to the crystal and keep it constant ( $3\text{ mA}$ ) throughout the experiment.
- Initially the temperature of the oven must be at room temperature ( $\sim 27^{\circ}C$ ).
- Switch on the oven to start increasing the temperature.
- Note the voltage and temperature at intervals of  $5^{\circ}C$  starting from room temperature.
- When temperature reaches  $140^{\circ}C$  switch off the oven and note the voltage and temperature for decreasing temperature till it reaches room temperature.
- Find the mean of the two voltages, for increasing and decreasing temperatures. Calculate  $\rho$  for each temperature.
- Convert the temperature scale from  $^{\circ}C$  to the Kelvin scale (K). The plot of  $\ln \sigma$  vs  $1/T$  should be a straight line. Calculate the slope ( $m$ ) of the straight line and finally the band gap  $E_g$  from the given formula

$$\sigma = \sigma_o \exp\left(-\frac{E_g}{2KT}\right) \quad (4.7)$$

## Observations

Sl.	Temp (T)	$1000/T$	$I$ during inc. temp.	Inc. volt.	Inc. V/I	$\rho$	$\sigma = 1/\rho$	$\ln \sigma$
	( $^{\circ}C$ )	( $K^{-1}$ )	(I) (mA)	(V) (mV)	( $\Omega$ )	( $\Omega$ m)	( $S$ m $^{-1}$ )	--

## Results

- 1.
- 2.

## Experiment 5

# Refractive index of glass with the help of a prism

### Purpose

- To understand the accurate leveling and focusing of a spectrometer.
- Investigation of the variation in the refractive index,  $\mu$  of a prism with wavelength  $\lambda$ .

### Apparatus

Spectrometer, prism, mercury light source, high voltage power supply, magnifying lens, spirit level, torch light etc.

### Theory

The fact that a prism is capable of dispersing light is due to the variation of its refractive index with wavelength. In this experiment the refractive index is obtained for a variety of wavelengths by measuring the *minimum deviation* angle of the prism for each wavelength.

To understand what is meant by the term *angle of minimum deviation*, consider Fig. 5.1. The incident parallel light beam is refracted by the prism in such a way that it is deviated by the angle  $\theta_d$  from the undeviated direction. The angle is known as the angle of deviation and varies with both the wavelength and the angle at which the incident light intersects the prism.

If the prism is rotated about the axis it is found that the angle of deviation changes but never becomes less than a certain minimum value,  $\delta_{min}$  known as the angle of minimum deviation i.e. no matter what the orientation of the prism, as long as it is in the path of the incident light beam, the light beam will be deviated through at least this angle. When the prism is oriented in such a way that the exit beam is deviated through the least possible angle  $\delta_{min}$ , then further rotation of the prism in either direction will cause the exit beam to move further away from the least deviated direction. Thus for each wavelength in a spectral light source, there is a variation of the angle of deviation,  $\theta_d$  with the angle of incidence,  $\theta_i$  and at some value of the angle of incidence, the angle of deviation reaches a minimum as seen in Fig. (5.3).

### Relation between $\mu$ and $\lambda$

The refractive index of the prism material,  $\mu$  is a function of the angle of minimum deviation ( $\delta_{min}$ ), the incident wavelength ( $\lambda$ ) and the prism refracting angle ( $A$ ). Thus,

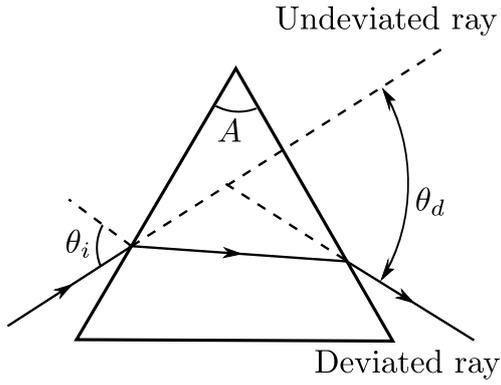


Figure 5.1: Deviation of monochromatic light ray due to prism.

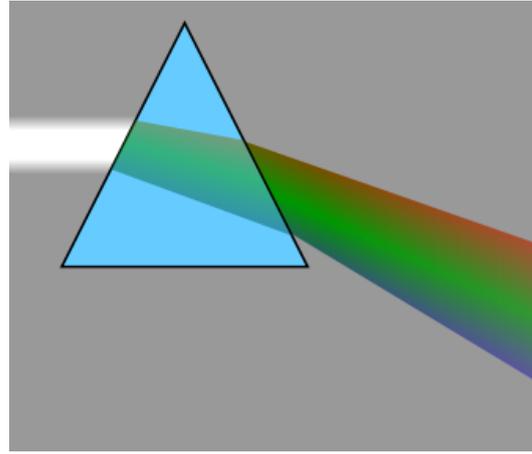


Figure 5.2: Spectrum due to a prism.

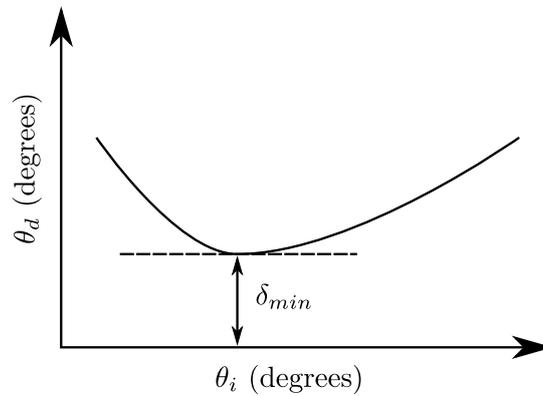


Figure 5.3: Variation of the angle of deviation ( $\theta_d$ ) with the angle of incidence ( $\theta_i$ ) for a particular wavelength.

by measuring  $\delta_{min}$  for a variety of wavelengths, the variation of  $\mu$  with wavelength may be determined.

To derive the exact relationship, consider the prism as seen in Fig. (5.4). It can be shown that the minimum value of the angle of deviation,  $\delta_{min}$  occurs when the ray passes through the prism symmetrically i.e. when the angle at which the light emerges is equal to the angle of incidence such that the ray passes parallel to the base of the prism as in Fig. (5.4). At each face the ray changes direction by  $\theta_i - \theta_r$  and so the total minimum deviation is

$$\delta_{min} = 2(\theta_i - \theta_r) \quad (5.1)$$

From Fig. 5.4, it is shown that the angle  $\angle MNO$  is the same as that of the refracting angle of the prism. Referring to the triangle LMN it is obvious, using trigonometry, that  $A = 2\theta_r$ . Snell's Law is of course  $\mu = \sin \theta_i / \sin \theta_r$  but  $\theta_i = \delta_{min}/2 + \theta_r$ , where  $\theta_r = A/2$  and hence we have

$$\mu = \frac{\sin((A + \delta_{min})/2)}{\sin(A/2)}. \quad (5.2)$$

An empirical equation of the form

$$\mu = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} \quad (5.3)$$

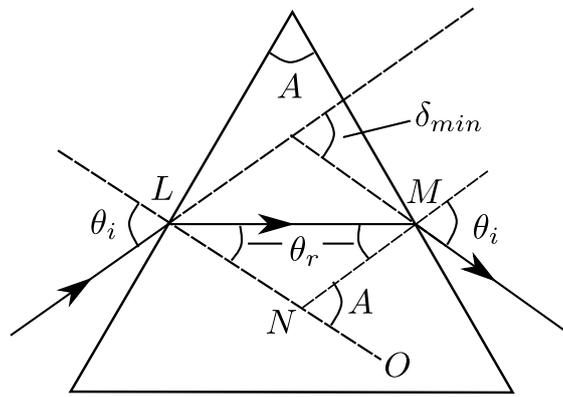


Figure 5.4: Condition for minimum deviation

was developed by Cauchy to describe the variation of  $\mu$  with wavelength. Where  $a$ ,  $b$  and  $c$  are constants and it is the purpose of this experiment to verify this equation (neglecting terms of higher order than the second) and to derive the constants  $a$  and  $b$  for the prism material.

**Note:** As the variation in refractive index over the whole of the visible is only of the order of 3% this means that  $\delta_{min}$  varies only very slowly with wavelength. Both a fair degree of experimental skill and great care in making the various measurements are necessary if reasonable results are to be attained.

## Experimental procedure

Initially make sure you understand what each component of the spectrometer as detailed in Fig. (5.5) does. The experimental setup consists of following parts. To obtain satisfactory

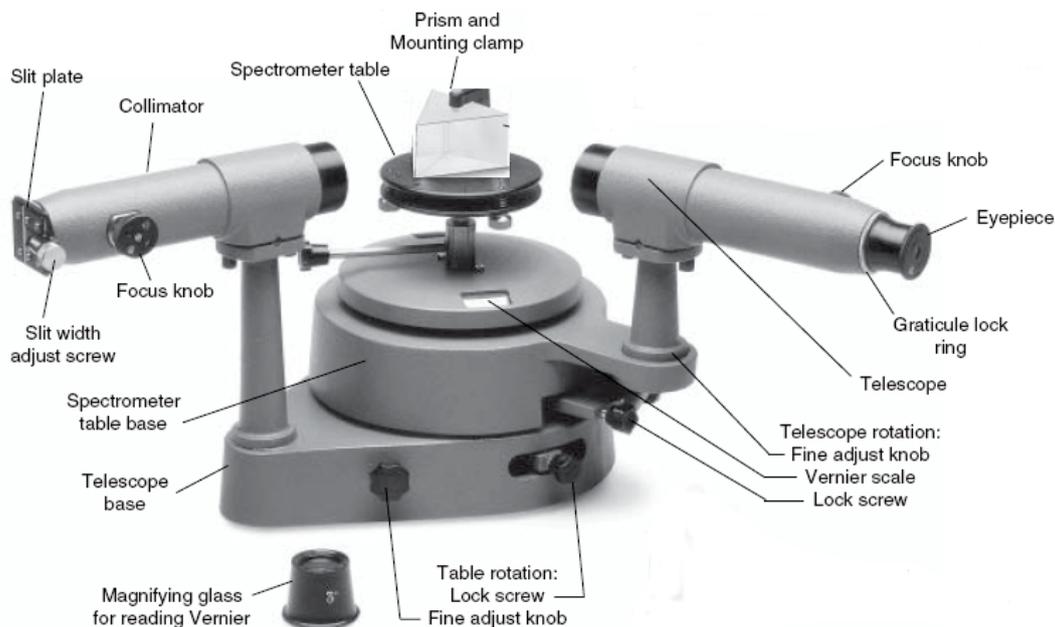


Figure 5.5: Spectrometer with its components

results the spectroscope requires some initial adjustments before the desired measurements can be performed. For this experiment great care must be taken in adjusting the

spectrometer so that the telescope is focused at infinity and the collimator set to give an accurately parallel beam. It is particularly important to ensure that the cross-hairs of the telescope are sharply visible and that no parallax exists between them and the spectral line images. The following steps should ensure this:

1. *Focusing the telescope:* Focus the telescope for the parallel rays from the distance object by sliding the eyepiece looking through telescope in and out, until a sharp image of object is seen. Due to the location of the laboratory this may not be possible so the building opposite may be used for this purpose.
2. *Levelling the collimator:* Place the spirit level on the collimator tube with its axis parallel to the axis of the tube. If the bubble in the collimator is found to be displaced from its central position, turn the levelling screws provided with the collimator tube, in the same direction to bring the bubble back to its central position. This makes the axis of the collimator tube horizontal.
3. *Levelling of the prism table:* There are three levelling screws A, B, C just below the prism table for levelling the table. There are parallel lines drawn on the prism table parallel to the line joining the screws B and C. Place the spirit level parallel to these lines and bring the bubble to the central position by turning the screws B and C equally in opposite directions. Now place the spirit level perpendicular to the line BC. If the bubble is not in the central position, then turn the A screw alone to bring the bubble in the center. Continue this for a couple of times until the bubble is in the center in both the positions. This makes the table vertical to the axis of rotation.
4. *Focusing the collimator:* Place a discharge lamp (Mercury lamp as a visible light source) in front of the spectroscope and turn the telescope until it is in line with and pointing directly at the collimator. Looking through the telescope and adjusting the position of the focusing screw on the collimator until a sharp image of the slit is observed in the telescope. The collimator now gives parallel rays which will fall on the prism.

### Finding the least count for the spectrometer

It should be noted by the student that 30 vernier scale divisions (VSD) coincides with 29 circular scale divisions (CSD). So,

$$30 \text{ VSD} = 29 \text{ CSD} \quad (5.4)$$

$$1 \text{ VSD} = \frac{29}{30} \text{ CSD} \quad (5.5)$$

Therefore, the least count

$$\text{LC} = 1 \text{ CSD} - 1 \text{ VSD} \quad (5.6)$$

$$= \left(1 - \frac{29}{30}\right) \text{ CSD} = \frac{1}{30} \text{ CSD} \quad (5.7)$$

Since  $1 \text{ CSD} = (1/2)^\circ = 30'$ , we have

$$\text{LC} = \frac{1}{30} \times 30' = 1' \quad (5.8)$$

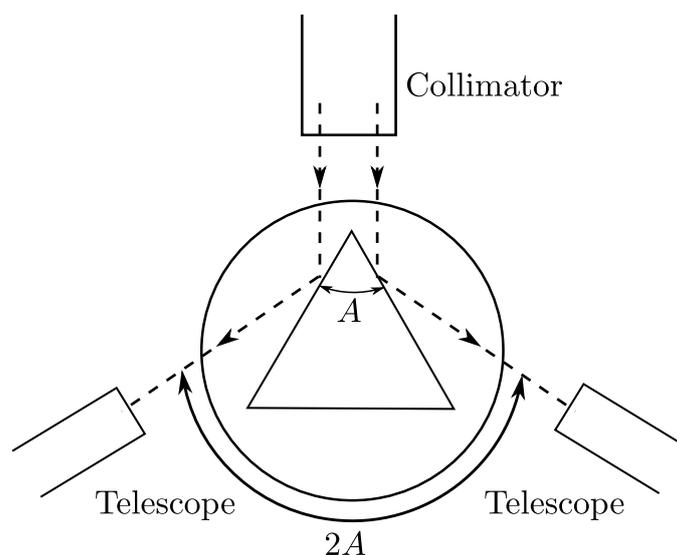


Figure 5.6: Measurement of the reflecting angle of prism.

### Measurement of the angle of prism ( $A$ )

- Set up the prism and spectrometer as in Fig. (5.6). Lock the prism table.
- Place the telescope cross-hairs in turn on the image of the slit reflected from surface  $AB$  and then surface  $AC$ .
- At each position record the angular position of the telescope on the vernier scale—the angle between the two positions of the telescope is  $2A$ , twice the apex angle of the prism and hence  $A$  can be found.
- Repeat above step 2 and 3 to get an average value for  $A(\approx 60^\circ)$ .

### Viewing the spectrum due to refraction

The telescope and prism are rotated until the spectrum formed by refraction is found. The approximate prism position is shown in Fig. 5.7.

Further rotation of the prism while viewing the spectrum through the telescope will result in reaching the angle of minimum deviation. This is where the spectral lines “turn back” on themselves i.e. move opposite to their initial direction of travel while the prism is still being rotated in the same direction.

Position the prism and telescope so that the spectral lines are at the angle of minimum deviation i.e. at the point where the spectral lines “turn back” on themselves.

Turning the prism towards the telescope, increases the angle of incidence, thus moving to the right hand side of  $\delta_{min}$  in the curve of Fig. (5.3). Conversely turning the prism towards the collimator, decreases the angle of incidence, hence moving through the angle of minimum deviation to the left hand side of the curve of Fig. 5.3.

### Measurement of the angle of minimum deviation, $\delta_{min}$ for each wavelength

1. Using the  $Hg$  spectral lamp, observe the first order field of view of refracted spectrum. Find the point of minimum deviation for the  $Hg$  spectrum. The approximate prism position is as shown in Fig. 5.7.

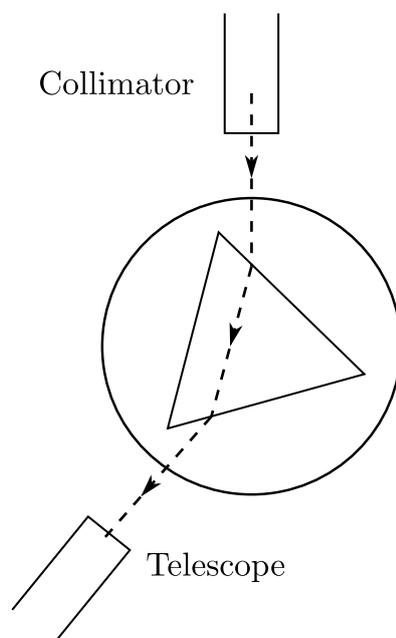


Figure 5.7: Prism position for viewing the spectrum due to refraction.

Lamp	Colour	Wavelength (nm)
Mercury	Violet	380 - 450
	Blue	450 - 495
	Green	495 - 570
	Yellow	570 - 590
	Orange	590 - 620
	Red	620 - 750
Sodium	Yellow ( $D_1$ )	589.6
	Yellow ( $D_2$ )	589.0

Table 5.1: Discharge lamp wavelengths

*(Remember minimum deviation corresponds to the point at which movement of the lines of the Hg spectrum over the field of view of the telescope is reversed, although direction of rotation of the telescope continues in the same sense.)*

- Several spectral lines should be in the field of view of the telescope. Position the telescope on the highest wavelength spectral line and lock the prism table and telescope. It is essential that the prism and prism table remain in this position for the remainder of the experiment.
- Using the telescope fine adjustment screw, position the crosshairs of the telescope accurately on the spectral line of interest and read the vernier to the nearest minute of arc.
- The above step can be repeated for the other lines in the field of view of the telescope there should be enough movement in the telescope fine adjustment screw to allow

positioning of the cross-hairs on all of the  $Hg$  spectral lines of Table 5.1 without unlocking the telescope again. If this is not the case, just unlock the telescope and reposition it such that the crosshairs of the eyepiece are on the spectral line of interest. It is imperative that the prism and prism table remain in their original fixed position.

5. Rotate the telescope anticlockwise until the undeviated image of the slit through the prism is in the field of view. Again position the crosshairs on the centre of the slit image and record the angular reading of the telescope on the vernier scale.
6. The actual value for  $\delta_{min}$  for each wavelength is the difference between the appropriate angular reading of the telescope position for minimum deviation and for the undeviated (straight through) position as seen in Fig. (5.1)

## Observation

### Measurement of angle of prism (A)

Least count of the spectrometer (l.c.) = .....

Sl.	Position I			Position II			$2A = \theta_1 - \theta_2$	Prism angle (A)
	CSR	VSR	Total reading ( $\theta_1$ )	CSR	VSR	Total reading ( $\theta_2$ )		
–	(deg)	–	(deg)	(deg)	–	(deg)	(deg)	(deg)
1								

Table 5.2: Table for measuring angle of prism (A). CSR - Circular scale reading, VSR - Vernier scale reading.

### Measurement of angle of minimum deviation ( $\delta_{min}$ )

Angle by undeviated ray ( $\theta'$ ) = ..... (CSR) + ..... (l.c.)  $\times$  ..... (VSR) = ..... (Total)

## Calculation

1. Calculate the refractive index  $\mu$ , of the prism material for each wavelength using Eq. 5.2. Tabulate also a corresponding set of values for  $1/\lambda^2$ .
2. Draw a graph of  $\mu$  vs  $1/\lambda^2$ .
3. Extract values for the Cauchy constants,  $a$  (intercept) and  $b$  (slope), of Eq. 5.3 from your graph. The least squares fitting routine can be used to get a more accurate value for  $a$  and  $b$ .

## Results

- Calculate the refractive index for different values of wavelengths.

Sl.	Colour	Angle by deviated ray			$\delta_{min} = \theta' - \theta$	$\mu$
		CSR	VSR	$\theta$		
–	–	(deg)	–	(deg)	(deg)	–
1	Violet					
2	Green					
3	Yellow					
4	Red					

Table 5.3: Table for measuring angle of minimum deviation. CSR - Circular scale reading, VSR - Vernier scale reading.

## Notes

### Subtraction of angles (Mathematical)

Try to subtract  $45^{\circ}25'$  from  $90^{\circ}15'$ . (Hint: Remember that  $1^{\circ} = 60'$ ).

### Note about calculators

- Some calculators are not able to handle degree and minutes. Make sure the degree minutes in these cases are converted to fractional degree via the conversion  $1^{\circ} = 60'$ .
- Make sure your calculator is set to degree and not to radian or gradient.

### Subtraction of angles (Geometrical)

Find the difference of angles  $\Delta$  for these cases

- $\theta_1 = 100^{\circ}$ ,  $\theta_2 = 10$
- $\theta_1 = 100^{\circ}$ ,  $\theta_2 = 350$

(Hint: If the difference between two angles ( $\Delta$ ) is more than  $180^{\circ}$ , subtract  $\Delta$  from  $360^{\circ}$ . See Fig. 5.8.)

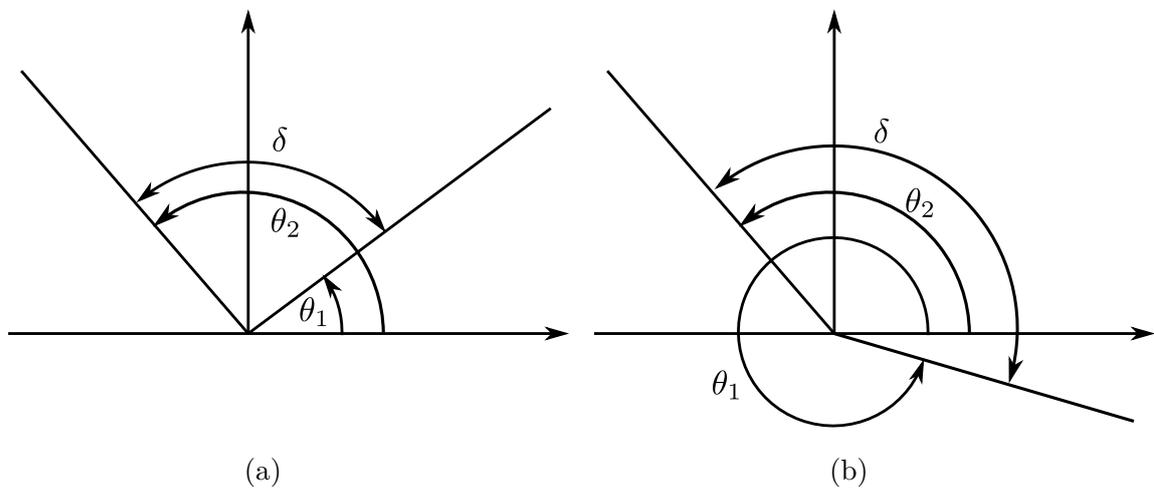


Figure 5.8: Difference of angles in the two cases should be as follows: (a)  $\Delta = |\theta_2 - \theta_1|$  and (b)  $\Delta = (360 - \theta_1) + \theta_2 = 360 - (\theta_1 - \theta_2)$ .

## Experiment 6

# Wavelength of sodium light by Newton's rings

### Purpose

To determine the wavelength of sodium light by measuring the diameters of Newton's rings

### Apparatus

Newton's ring microscope, sodium vapour lamp, circular slit plate, light emitting diode source

### Theory

Fig. 6.1 shows the experimental setup of Newton's ring. The formation of maximum intensities at some points and minimum intensities at the other due to the superposition of two coherent light waves (of same frequencies and constant phase difference) is called interference of light. The interference fringes are observed as an alternate pattern of bright and dark fringes. The interference at a point where the intensity of light is maximum, is called constructive interference (corresponds to bright fringe). For constructive interference, the two waves should have either same phase or a constant phase difference of

$$\phi = 2n\pi, \quad (6.1)$$

where  $n = 0, 1, 2, \dots$ . Phase difference ( $\phi$ ) and path difference ( $\Delta$ ) are related by the equation

$$\phi = (2\pi/\lambda)\Delta, \quad (6.2)$$

where  $\lambda$  is the wavelength of the incident light. So, for constructive interference the path difference between the light waves should be

$$\Delta = n\lambda. \quad (6.3)$$

The interference at other point where the intensity of light is minimum, is called destructive interference (corresponds to dark fringe). For destructive interference, the two waves should have either same phase or a constant phase difference of

$$\phi = (2n + 1)\pi, \quad (6.4)$$

where  $n = 0, 1, 2, \dots$  or a constant path difference of

$$\Delta = (2n + 1)\lambda/2. \quad (6.5)$$

Interference fringes are obtained by dividing the single coherent source into two sources. This can be achieved by one of the following methods

1. by division of wave front, that is by taking (or considering) two secondary wavelets on the same wave front and superposing them
2. by division of amplitude, that is by separating the amplitude of single wave and reuniting them.

In the case of Newton's ring interference is due to division of amplitude.



Figure 6.1: Experimental setup of Newton's ring

When light is incident on a thin film (thickness of the order of wave length of the incident light), it suffers partial reflection and partial transmission at both upper as well as lower surfaces of the thin film. The transmitted light ray again suffers reflection at the lower surface. Interference occurs between the rays in the reflected and transmitted parts.

Similarly, in a wedge-shaped film, partial reflection as well as partial transmission also takes place. Moreover, the path difference changes from point to point which results into an interference fringe.

Fig. 6.2 shows an wedge-shaped air film formed between the convex and plane glass plate inclined at an angle say  $\theta$ . The refractive index of the film is  $\mu$ . Ray  $AB$  is incident from a broad monochromatic source almost normally on the film. It suffers partial reflection (ray  $BE$ ) and partial transmission (ray  $BC$ ) on the convex surface. Ray  $BC$  again suffers partial reflection (ray  $CF$ ) and partial transmission (not shown) on the plane surface at  $C$ .

The bright rings in the Newton's ring, as shown in Fig. 6.3, are due to constructive interference between the reflected light rays  $BE$  and  $CF$ . The dark rings are caused by destructive interference between the same light rays  $BE$  and  $CF$ .

For a wedge-shaped thin film, the path difference between the rays  $BE$  and  $CF$  is given by

$$\Delta = 2\mu t \cos \alpha \quad (6.6)$$

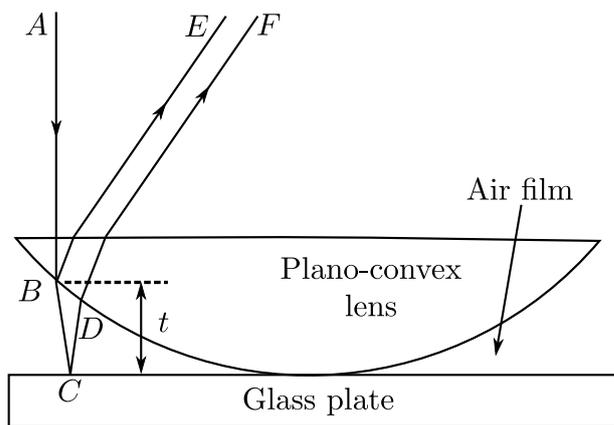


Figure 6.2: Schematic diagram of the light rays in Newton's ring

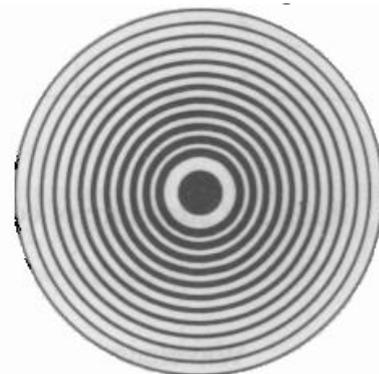


Figure 6.3: Newton's ring

Where  $t$  is the thickness of the film at  $B$  (or at  $D$ ) and  $\alpha$  is the angle of refraction at  $B$ . Since the angle of incidence is almost normal, we can assume  $\cos \alpha \approx 1$ . Note that here we ignore the reflections from top of the plano-convex lens and bottom of the plane circular glass plate since these reflections just contribute to the overall glare. The reflections of interest are only those involving the surfaces in contact.

Now by Stoke's law, there is no phase change at the glass-air interface of the convex lens (because the wave is going from a higher to a lower refractive index medium), whereas the reflection at the air-glass interface of the plane glass plate undergoes an additional path difference of  $\lambda/2$ . Therefore, the net path difference is

$$\Delta + \frac{\lambda}{2} = 2\mu t + \frac{\lambda}{2} \quad (6.7)$$

Since for bright fringe, net path difference is  $n\lambda$  we have,

$$2\mu t = (2n + 1)\frac{\lambda}{2}. \quad (6.8)$$

Similarly, for dark fringe, the net path difference is  $(2n + 1)\lambda/2$  and thus we have,

$$2\mu t = n\lambda. \quad (6.9)$$

At the centre, no reflection occurs since the two glass surfaces are in intimate contact i.e.  $t = 0$  or  $2\mu t = 0$ . This is the condition for dark fringe. Hence the center of the pattern is always dark.

In the right-angled triangle  $OAB$  of Fig. 6.4,

$$\begin{aligned} OB^2 &= OA^2 + AB^2 \\ \text{or, } R^2 &= (R - t)^2 + r_n^2 \\ \text{or, } r_n^2 &= 2Rt \end{aligned} \quad (6.10)$$

for  $t^2 \ll 2Rt$ . Thus,

$$\begin{aligned} t &= r_n^2/2R \\ \text{or, } t &= D_n^2/8R \end{aligned} \quad (6.11)$$

where,  $r_n$  = radius of  $n^{\text{th}}$  ring,  
 $D_n$  = diameter of the  $n^{\text{th}}$  ring,  
 $R$  = radius of curvature of the plano-convex lens.

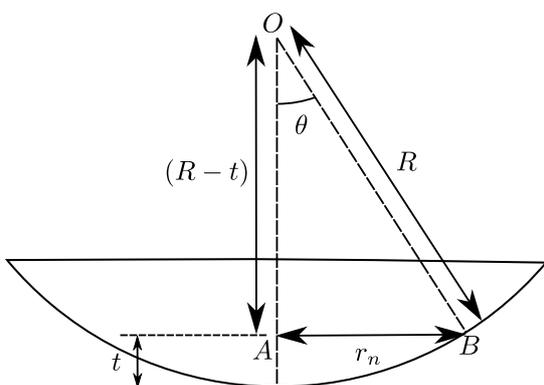


Figure 6.4: Schematic diagram of plano-convex lens

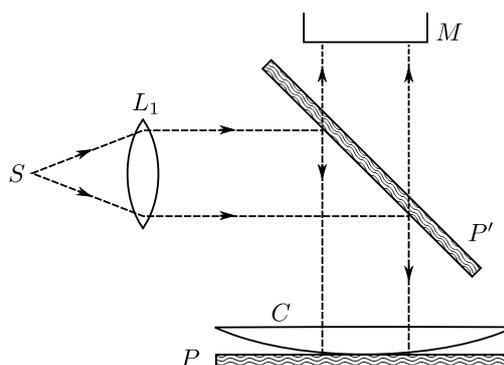


Figure 6.5: Newton's ring assembly

In practice, it is not possible to find the exact centre of the bull's eye in order to obtain  $r_n$ . Rather, the traveling microscope can measure an approximate diameter  $D_n$  for the interference ring. Therefore, substituting the value of  $t$  from Eq. 6.9, we obtain the diameters of the  $n^{\text{th}}$  dark fringe as

$$D_n^2 = \frac{4nR\lambda}{\mu} \quad (6.12)$$

Since the human eye is more sensitive to small changes in low intensity, we will measure positions of dark fringes throughout the experiment.

## Procedure

1. The Newton's ring microscope has two parts, (i) microscope with horizontal measurement and (ii) a Newton's ring assembly. First detach the Newton's ring assembly and clean the adjustable glass plate, plano-convex lens and its adjoining glass plate with a clean cloth.

Note: Do not detach the plano-convex lens from glass plate frequently. It will disturb the measurements.

2. Replace the plano-convex lens over the glass plate and tight them carefully with the help of three leveling screws (if present). An interference ring pattern can be observed with the naked eye.

Precaution: Avoid over-tightening of the screws. Tight the screws to bring the central fringe at the centre. Adjust it's diameter to around 3 mm.

3. Arrange the Newton's ring assembly as shown in Fig. 6.5. Note that the glass plate  $P'$  should be inclined at  $45^\circ$  with respect to the vertical plain.
4. First connect the sodium vapour lamp power supply with mains. Then connect it with the light source box with the help of mains cord. Then switch ON the power supply.

Precaution: Never connect the sodium vapour lamp directly to the main power supply.

5. Wait for 30 minutes till the lamp glow bright yellowish.
6. Insert circular slit plate into the slit-holder. Adjust to fully illuminate glass plate  $P'$  inclined at  $45^\circ$ .

7. Calculate the least count of the traveling microscope ( $M$ ). If  $p$  is the pitch of the micrometer screw in cm, and  $m$  is the number of divisions on the circular scale, then least count is  $p/m$  in cm.
8. Take a view through the eye piece of the tube as shown in Fig. 6.6.
9. There are two type of movements provided in the microscope, coarse and fine. Align the microscope tube, with the help of coarse movement knob nos. 2 and 4 as shown in Fig. 6.6, to bring it over the glass plate  $P'$ .

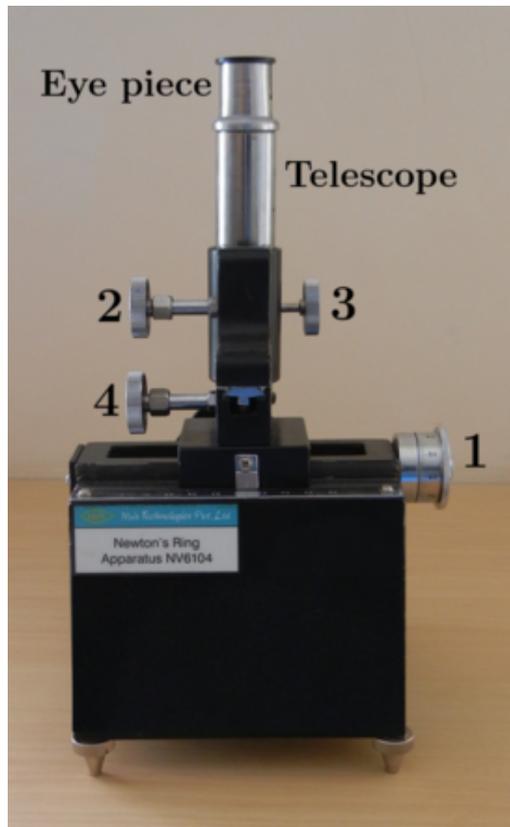


Figure 6.6: Experimental setup of Newton's ring showing the screws

10. Now move the microscope tube with the help of fine movement knob no. 3 close to the plate  $P'$  to obtain clear image of surface. Slowly move towards upward direction. Newton's rings pattern is observed. Adjust by moving the microscope to and fro, if necessary, to view the full pattern. Adjust further for better contrast between bright and dark fringes.
11. Bring the cross-wire, using knob no. 1 shown in Fig. 6.6, in the central fringe such that their centre should coincide with each other.
12. Slide the cross-wire to the left till the vertical cross-wire line lies tangentially at the 20th ring. Note the reading on the main and circular scale using the light emitting diode.
13. Now slowly slide the microscope to the right and note the reading when the vertical cross-wire lies tangentially at the 16th, 12th, 8th and 4th rings respectively.
14. Keep sliding the microscope to the right and again note the readings when the vertical cross-wire lies tangentially at the 4th, 8th, 12th, 16th and 20th rings respectively.

Sl.	Ring no. ( $n$ )	LHS			RHS			$D = b - a$ (cm)	$D^2$ (cm <sup>2</sup> )
		MSR	CSR	Total ( $a$ ) (cm)	MSR	CSR	Total ( $b$ ) (cm)		
1	20								
2	16								
3	12								
4	8								
5	4								

Table 6.1: Table for measurement of the diameter of the dark rings. MSR - Main scale reading, CSR - Circular scale reading.

15. The radius of curvature ( $R$ ) of the plano-convex lens is 100 cm which can be calculated using the following formula

$$\frac{1}{f} = (\mu_g - 1) \left( \frac{1}{R} - \frac{1}{R_p} \right), \quad (6.13)$$

where,  $f$  = focal length of the lens = 200 cm,  
 $\mu_g$  = refractive index of the material of the lens (i.e glass) = 1.5,  
 $R$  = Radius of curvature of one side the convex side of the plano-convex lens,  
 $R_p$  = Radius of curvature of plane side of the plano-convex lens  $\rightarrow \infty$ .

16. Plot the graph  $D^2$  as a function of  $n$ . This should be a straight line passing through the origin (See Eq. 6.12).  
17. Find the slope of the line from the graph.  
18. Find the wavelength of sodium light from this slope using Eq. 6.12.

## Results

The wavelength of sodium light is \_\_\_\_\_ nm.

# Experiment 7

## Helmholtz coil

### Purpose

To study the magnetic field produced by current carrying coils.

### Apparatus

Helmholtz coils, connecting wires, gaussmeter, regulated power supply, measuring scale, etc.

### Theory

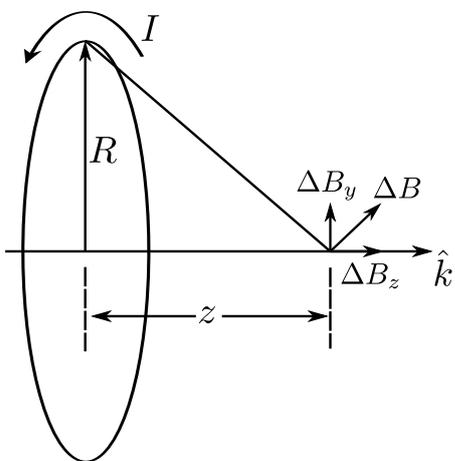


Figure 7.1: Magnetic field perpendicular to a current carrying coil.

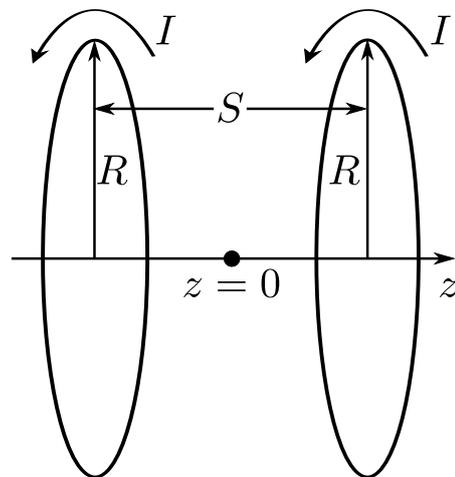


Figure 7.2: Helmholtz coil.

The magnetic induction of a circular coil of radius  $R$ , carrying a current  $I$ , at a distance  $z$  from the center of the loop along the axis (see Fig. 7.1) is given by

$$\vec{B}(z) = \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \hat{k} \quad (7.1)$$

where  $\mu_0$  is the permeability of free space. At  $z = 0$ ,  $\vec{B}(0) = \mu_0 I / (2R) \equiv B_{10}$ .

If there are two such parallel coils at a distance  $S$  such that the current flows in the same direction in both the coils (see Fig. 7.2), then magnetic field adds in the space

between them. Then we have

$$\vec{B}(z) = \frac{\mu_0 I R^2}{2} \left[ \frac{1}{\left[ R^2 + \left( \frac{S}{2} + z \right)^2 \right]^{3/2}} + \frac{1}{\left[ R^2 + \left( \frac{S}{2} - z \right)^2 \right]^{3/2}} \right] \quad (7.2)$$

$$= B_{10} \left[ \frac{1}{\left[ 1 + (0.5 st + zt)^2 \right]^{3/2}} + \frac{1}{\left[ 1 + (0.5 st - zt)^2 \right]^{3/2}} \right] \quad (7.3)$$

where,  $st = S/R$ ,  $zt = z/R$  and  $B_{10} = \mu_0 I / (2R)$ .

At the midpoint  $\partial \vec{B} / \partial z$  is zero. Further  $\partial^2 \vec{B} / \partial z^2$  is also equal to zero at  $z = 0$  if  $S = R$ . Because of these properties, the axial magnetic field is fairly constant over certain region in the middle of the pair of coils. This arrangement is very popular in producing uniform axial fields in regions easily accessible to experimental situations needing such uniformity.

In this experiment we will study the magnetic field variations for such a pair of Helmholtz coils. The magnetic field is measured using a Hall probe connected to a gaussmeter.

## Construction of Helmholtz coils

The two coils are made of copper wire windings in 14 layers, each of 11 turns, such that the total number of turns ( $n$ ) = 154. The sockets of the coil winding are cast into the plastic foot of the coil and the connecting leads can be used to connect the coils in parallel or series as required. The sockets are numbered (1, 2) to make it easier to wire the coils. See Fig. 7.3. In the Helmholtz arrangement, the coils are positioned by three spacer rails so

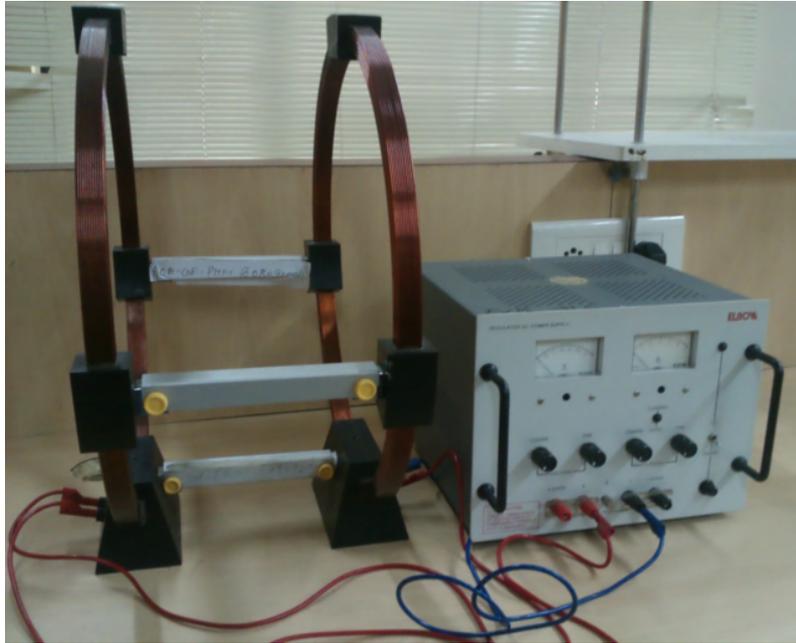


Figure 7.3: Experimental setup of Helmholtz coil.

that their axial spacing is equal to the average coil radius. The rails can be removed after undoing knurled screws, allowing coils to be used individually or with variable spacing.

The coil of the diameter	400 mm
No of turns per coil	154
Coil resistance	2.1 $\Omega$

## Procedure

- Calibrate the Hall probe attached to the gaussmeter.
- Connect the coils with the power supply in such a way that both the coils have the same current in proper direction. *In no case the current should exceed 3A.*
- Place the hall probe perpendicular to the magnetic field and measure the readings at regular intervals.

## Observation

We study the magnetic field in current carrying coil (Helmholtz coil) in three different scenarios:

**(A) Magnetic field along the axis of the coils when current is flowing in the same direction in both the coils**

Sl.	Distance (cm)	Magnetic field (Gauss)	
		$I_1 = \dots$ A	$I_2 = \dots$ A

**(B) Magnetic field along the axis in a single coil**

Sl.	Distance (cm)	Magnetic field (Gauss)	
		$I_1 = \dots$ A	$I_2 = \dots$ A

**(C) Magnetic field along the diameter in a single coil**

Sl.	Distance (cm)	Magnetic field (Gauss)	
		$I_1 = \dots$ A	$I_2 = \dots$ A

Plot the intensity of magnetic field with distance along the coil for different current value for above describe three case.

## Results

- 1.
- 2.

## Experiment 8

# Electromagnetic induction

### Purpose

- To study the flux and emf in the coil as a function of time
- To study the maximum emf and total flux as a function of the velocity of the magnet.
- To demonstrate damping due to induced current.

### Apparatus

Faraday setup, diode, capacitor, breadboard, connecting wire, CRO etc.

### Theory

Faraday's law of electromagnetic induction tells us that a change in magnetic flux gives rise to an induced emf  $\varepsilon$  given by

$$\varepsilon = -\frac{d\phi}{dt}, \quad (8.1)$$

where  $\phi$  is the magnetic flux. A simple apparatus has been designed, whose schematic

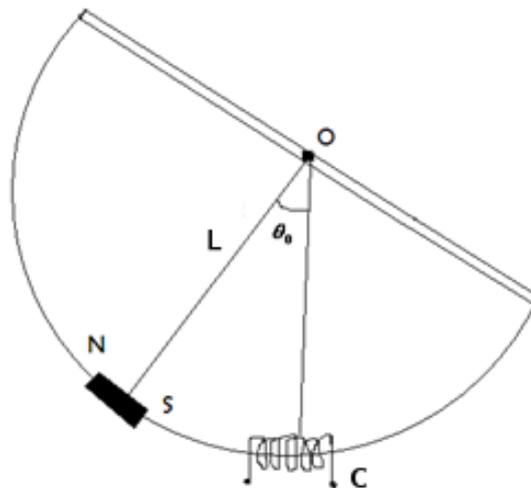


Figure 8.1: Schematic of the coil moving in and out of the magnetic field.

diagram is shown in Fig. (8.1), enables us to change  $\theta$  at different rates through a coil of

suitable area of cross-section. A rigid semicircular frame of aluminium is pivoted at the centre of the semicircle. The whole frame can oscillate freely in its own plane, about a horizontal axis passing through its centre. A bar magnet can be mounted at the centre of the arc and the arc passes through a coil  $C$ .

It is very instructive to study the emf, induced in the coil as the magnet passes through the coil while oscillating. In this experiment we will use a computer to monitor emf induced as a function of time.

The rate of change of flux through the coil is essentially proportional to the velocity of the magnet, as it passes through the coil. Choosing different amplitudes of oscillations can vary the velocity.

If  $I$  is the moment of inertia of the oscillatory system and  $\omega$  is the angular velocity of the magnet, then the kinetic energy of the system is  $I\omega^2/2$  and potential energy can be represented by  $MgL(1 - \cos\theta)$  at any instant of time, where  $L$  is the effective length of the corresponding simple pendulum. If  $\theta_o$  is the maximum angular amplitude and  $\omega_{max}$  is the maximum value of angular velocity, then

$$\begin{aligned} \frac{1}{2}I\omega_{max}^2 &= MgL(1 - \cos\theta_o) \\ \text{or, } \omega_{max}^2 &= \frac{2MgL}{I}(1 - \cos\theta_o) \end{aligned} \quad (8.2)$$

The motion can be regarded approximately as simple harmonic and its time period is given by

$$T = 2\pi\sqrt{\frac{I}{MgL}} \quad (8.3)$$

From Eq. (8.2) and (8.3), we get

$$\omega_{max} = \frac{4\pi}{T} \sin(\theta_o/2) \quad (8.4)$$

$$v_{max} = \frac{4\pi}{T} L \sin(\theta_o/2) \quad (8.5)$$

where  $v_{max}$  is the maximum linear velocity associated with  $\omega_{max}$ . Angular amplitude  $\theta_o$  is directly measured from the instrument. Velocity is computed by measuring  $T$  and  $\theta_o$ .

## Procedure

### 1. Charging of capacitor to obtain $\varepsilon_{max}$

The induced emf can be measured by using a simple circuit as shown in Fig. 8.2. The induced emf in the coil charges a capacitor  $C$ , through a resistance  $R$  and a diode  $D$  and the voltage developed across  $C$  is measured by voltmeter  $V$ . The diode current can flow only if the voltage at  $A$  is greater than  $B$ . Thus once a capacitor attains a voltage  $\varepsilon$ , current can flow through the capacitor only if the induced emf is greater than  $\varepsilon$ . If the time constant  $RC$  is not small compared to the time taken for the magnet to cross the coil, the capacitor does not get fully charged in AC signal oscillation. It may take several oscillations to do so.

Connect a resistor, diode and a capacitor given to you in series with the coil. Observe the signal across resistor, diode and the capacitor as a function of time.

Calculate  $v_{max}$  using Eq. (8.5) and plot a graph between  $\varepsilon_{max}$  vs  $v_{max}$ .  $\varepsilon_{max}$  is the maximum potential obtained in the CRO.

### 2. Induced emf as a function of velocity

You can use the computer interface provided to measure the voltage as a function of time. The instructor will explain you how to use the software.

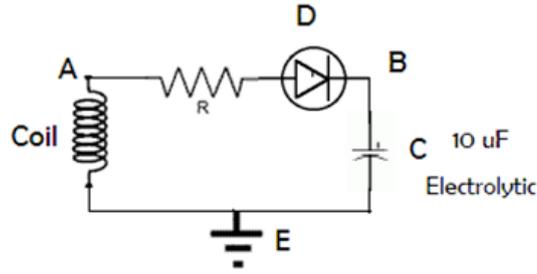


Figure 8.2: Circuit diagram for charging of a capacitor

- Ensure that the support for the apparatus is vertical by adjusting levelling screws. Adjust the weights  $W_1$  and  $W_2$  mounted on the horizontal bar to make zero of the scale as the mean position. Centre of the magnet must be inside the coil.
- **Measure time period  $T$ :** First find out the time period of the oscillation  $T$  for the apparatus. Connect the terminals of the coil to interface (COBRA 3), and record couple of oscillations by releasing the magnet from small initial amplitudes. Measure the time period from the plots on your computer screen. Make sure you account for a whole one cycle while measuring the  $T$ .
- **Plot of  $t$  vs  $\phi(t)$ :** Record one or two oscillations. Focus on only one of them by using magnification button. Use the integration feature of the software to obtain flux  $\phi$  as a function of time. You can integrate only half of the pulse, since the pulse is highly symmetric. Plot this on a graph paper for the complete pulse.
- $v_{max}$  **dependence of slope of  $\varepsilon(t)$  at mean position and  $\phi$ :** The emf induced in the coil can be written as

$$\varepsilon = - \left( \frac{d\phi}{d\theta} \right) \frac{d\theta}{dt} = -\omega \frac{d\phi}{d\theta} \quad (8.6)$$

Note that when the magnet is at its mean position, then  $\omega = \omega_{max}$  or velocity is at its maximum since  $V_{max} = \omega_{max} R$ . However,  $d\phi/d\theta = 0$  at that point. Hence emf will go through a zero corresponding to the mean position. Also note that

$$\left( \frac{d\varepsilon}{dt} \right)_{V_{max}} = - \left( \frac{d^2\phi}{d\theta^2} \right)_{v_{max}} \omega_{max}^2 \quad (8.7)$$

Hence a plot of the slope of  $\varepsilon(t)$  at the zero, corresponding to the mean position against  $v_{max}^2$  would be linear. The proportionality constant depends only on the geometry of the coil and the magnet.

For calculating  $\Phi$  use “Show integral” mode as before.

### 3. Electromagnetic damping in an oscillating system

We observe that the successive oscillations are not of the same amplitude. This is due to damping. Possible sources are: (i) air resistance, (ii) friction at the point of suspension, and (iii) induced emf (Lenz’s law).

The system (for small  $\theta$ ) and for damping proportional to velocity would satisfy the equation

$$I \frac{d}{dt} \left( \frac{d\theta}{dt} \right) + k \frac{d\theta}{dt} + \lambda \theta = 0 \quad (8.8)$$

where  $I$  is moment of inertia about origin,  $k$  is damping coefficient and  $\lambda\theta$  is restoring couple ( $Mgl\theta$ ), if treated as a simple pendulum of length 1.

The amplitude would exponentially decay only if  $k$  is a constant and damping term depends linearly in velocity. Record a large number of oscillations starting from initial amplitude of 300 to study the damping behaviour in the absence of induced current in the coil. The plot seen on the screen may not be correct representation of data since the number of points to be plotted is too large. Therefore divide the time axis to approximately 8 to 10 zones and take data after magnifying 1 pulse from each zone. Plot  $\epsilon_{max}$  and  $(d\epsilon/dt)_{(v_{max})}$  as a function of time or number of oscillations. From your data calculate  $Q$  of this oscillator using  $A = A_0 e^{rt/2}$  and  $Q = \omega_0/r$ .

Now, connect a resistor of about  $220 \Omega$  (the coil resistance is around  $900 \Omega$ ) in series with the coil and record voltage dropped across the resistor as a function of time (for large number of oscillations as in the previous case). Repeat analysis of data as above.

#### 4. Useful features of the software measure:

It is easy to use the software given to you. Take a few minutes to summarize yourself with it before going to the detailed experiments. All you have to do is to click the required icon given at the top. Some of the important ones are as follows:

**ARROW:** In this mode simply point the cursor at the required point to obtain values of the coordinates.

**MARK:** Use this mark a portion of the curve. The x-coordinate of the mark portion are shown on the bottom. The marked portion is highlighted in a different colour.

**SURVEY:** You can adjust the left bottom and right top coordinates of the cursor box to obtain coordinates and their differences in this mode. You can use this to calculate slopes around a point.

**SHOW INTEGRAL:** Mark the portion of the curve for which you need to calculate the integral and then click this icon to obtain the value. If you need to start from the origin, each time, take the cursor out of the plotting area and drag it across the origin to ensure that starting point is the same.

**SLOPE:** Mark the required portion of the curve for which you need the slope and then click this icon to get slope. However, we recommend use of survey mode to get slope more accurate.

## Observations

Sl.	$\theta_0$ (deg)	1		2		3		Avg $T_{20}$ (sec)	T (sec)	$\epsilon_{max}$ (V)	$v_{max}$ (m/s)
		$T_{20}$ (sec)	$\epsilon_{max}$ (V)	$T_{20}$ (sec)	$\epsilon_{max}$ (V)	$T_{20}$ (sec)	$\epsilon_{max}$ (V)				
1											
2											
3											
4											
5											

Sl.	Angle $\theta_o$ (degree)	Slope = $d\varepsilon/dt$	$v_{max}^2$	$\Phi(v_{max})$
1				
2				
3				
4				
5				

## Plots

1.  $\varepsilon_{max}$  vs  $v_{max}$
2.  $\left(\frac{d\varepsilon}{dt}\right)_{max}$  vs  $v_{max}^2$  and report  $\Phi(v_{max})$ .
3.  $\varepsilon_{max}$  vs  $\left(\frac{d\varepsilon}{dt}\right)_{max}$

## Result

Write down the conclusion in your own words by analysing the graphs.

# Experiment 9

## Mechanical waves

### Purpose

- Study wavelength ( $\lambda$ ) as function of frequency ( $\nu$ ) and to find out the phase velocity  $v_p$  of a traveling wave in a string.
- To measure linear mass density  $\mu$  of the string.

### Apparatus

Function generator, amplifier, mechanical oscillator, rubber rope, measuring tape, support rod, support base, and weights.

### Theory

A wave is an oscillation which propagates itself in space and time and usually periodically through matter and space. One can differentiate between transverse and longitudinal waves. In the case of transverse waves, the oscillation is perpendicular to the direction of the propagation of the wave. In the case of longitudinal waves, the oscillation and the propagation are in the same direction.

Our goal here is to find out the phase velocity of a wave. In order to calculate the velocity we need to know the frequency and the wavelength. Frequency is generated by function generator and is an independent variable here. So our main task is to calculate wavelength of the wave. Here in this experiment we calculate wavelength using a novel technique.

A standing wave is created by reflecting the wave from its opposite end. The distance between the nodes is measured and thus the wavelength is calculated.

A typical harmonic wave can be represented as,

$$y = A \sin(kx - \omega t) \tag{9.1}$$

where,  $y$  is the displacement of the particle from its mean position at a position  $x$  and at a time  $t$ .

$A$  is the amplitude of the oscillation.

$k$  is called the wave number and is related to the wavelength  $\lambda$  by the relation  $k = 2\pi/\lambda$ .

$\omega$  is called the angular frequency (measured in radians per meter) and is  $2\pi$  times the frequency.

Now consider two transverse waves having same amplitude, frequency, and wavelength but travelling in opposite directions in the same medium

$$y_1 = A \sin(kx - \omega t)$$

and

$$y_2 = A \sin(kx + \omega t) \tag{9.2}$$

where  $y_1$  represents a wave traveling in the  $+x$  direction and  $y_2$  represents a wave traveling in  $-x$  direction. Adding these two functions gives the resultant wave function  $y$

$$y = y_1 + y_2 \tag{9.3}$$

$$= A \sin(kx - \omega t) + A \sin(kx + \omega t)$$

$$y = 2A \sin(kx) \cos(\omega t) \tag{9.4}$$

This represents a wave function of standing waves. The speed of a wave on a string which is under tension  $T$  and having a mass per unit length  $\mu$  is given by

$$v_p = \frac{\omega}{k} = f\lambda = \sqrt{\frac{T}{\mu}} \tag{9.5}$$

and is called the phase velocity.

## Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 9.1 while Fig. 9.2 shows the various instruments of the experiment.

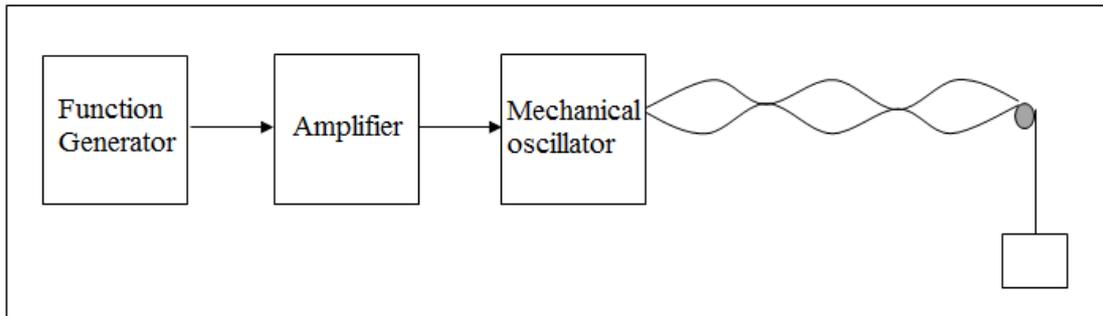


Figure 9.1: Schematic of standing wave generation

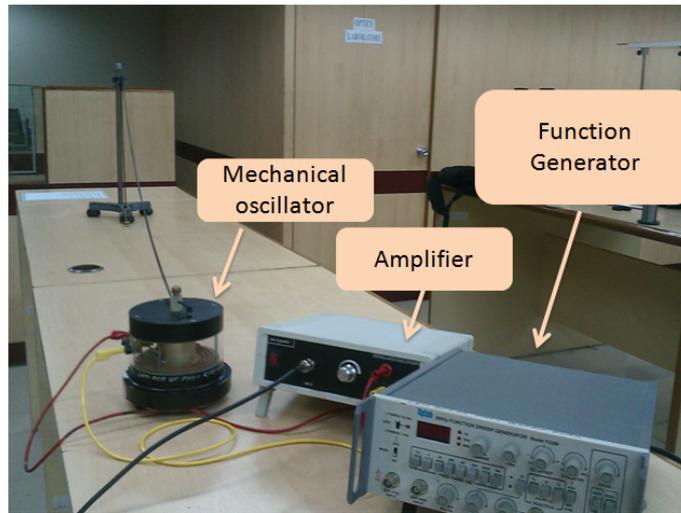


Figure 9.2: Experimental setup

## Observation

For a given setup, record

1. Frequency from the function generator ( $10\text{ Hz} - 25\text{ Hz}$ ).
2. Tension from the weight attached to the rope through the pulley.
3. Wavelength from the position of the nodes.

For constant mass  $m = \dots\dots\dots$  kg

Sl.	Frequency ( $f$ ) (Hz)	Number of loops ( $n$ )	Length ( $L$ ) (cm)	$\lambda = 2L/n$ (cm)	$1/\lambda$ ( $\text{cm}^{-1}$ )
1					
2					
3					
4					

For varying mass

Sl.	Mass ( $m$ ) (Kg)	Frequency ( $f$ ) (Hz)	$T = mg$ (N)	Number of loops ( $n$ )	Length ( $L$ ) (cm)	$\lambda = 2L/n$ (cm)	$v_p = f\lambda$ (cm/s)	$v_p^2$ (cm/s) <sup>2</sup>
1								
2								
3								
4								

## Calculation

1. Plot the  $1/\lambda$  vs frequency graph. From this graph, the phase velocity  $v_p$  should be determined. Keep the tension in the string constant i.e. mass is constant.

2. The phase velocity  $v_p$  of the rope waves, which depends on the tensile stress ( $T$ ) on the rope, is to be measured for a given frequency. Plot  $v_p^2$  vs  $T$  and hence find the mass/unit length of the string using Eq. (9.5).

## Results

1. Phase velocity (for constant mass)  $v_p = \dots\dots\dots$
2. Mass per unit length (for constant frequency)  $\mu = \dots\dots\dots$

# Experiment 10

## Fraunhofer Diffraction

### Purpose

- To understand what is meant by Fraunhofer diffraction.
- To observe single slit diffraction patterns and plot the intensity profile of the pattern.
- Determine slit width from the diffraction formula.

### Apparatus

Digital Multi-meter (DMM), He-Ne laser source, sliding detector (photocell), optical rail and mounts.

### Theory

Diffraction is the wave phenomenon which describes the deviation from straight line propagation of a wave when it encounters an obstruction. In the case of light waves both opaque and transparent obstacles cause this effect which results in *shadow patterns* on a screen which are quite different from those expected if light travelled only in straight lines.

There are basically two categories of diffraction effects. The first is Fraunhofer diffraction, which occurs when the waves incident on the slit and the screen (detector) are plane waves. This diffraction is produced when both the light source and screen are effectively at an infinite distance from the given obstacle. Fresnel diffraction is the second type and refers to diffraction produced when either the source or screen or both are at finite distances from the obstacle.

We can observe Fraunhofer diffraction experimentally by using a collimated light source and (i) placing the viewing screen at the focal plane of a convex lens located behind the obstacle or (ii) by placing the screen at a large distance from the obstacle. The schematic of a single slit diffraction apparatus is shown in Fig. 10.1.

In this experiment we concentrate on Fraunhofer diffraction patterns although you can observe the different patterns produced by Fresnel diffraction by placing the viewing screen close to the diffraction slit used.

Fig. 10.1 shows a plane wave of wavelength  $\lambda$  incident on a slit width  $a$ . The diffraction pattern, intensity versus  $y$  is plotted in the figure. Wave theory predicts that the Fraunhofer diffraction pattern intensity due to a rectangular slit will be of the form

$$I = I_o \frac{\sin^2 \beta}{\beta^2} \quad (10.1)$$

where  $\beta = (ka \sin \theta)/2$ ,  $k = 2\pi/\lambda$ ,  $a =$  slit width and  $\theta =$  angle formed by the light ray with respect to the system central axis. The minima in the diffraction pattern occurs when  $I(\theta) = 0$ . This condition requires that

$$a \sin \theta_m = m\lambda \quad (10.2)$$

where,  $m$  is the order number in diffraction pattern and  $\theta_m$  is angle measured with respect to system central axis to the  $m$ th order minima. The shape of this pattern is shown in

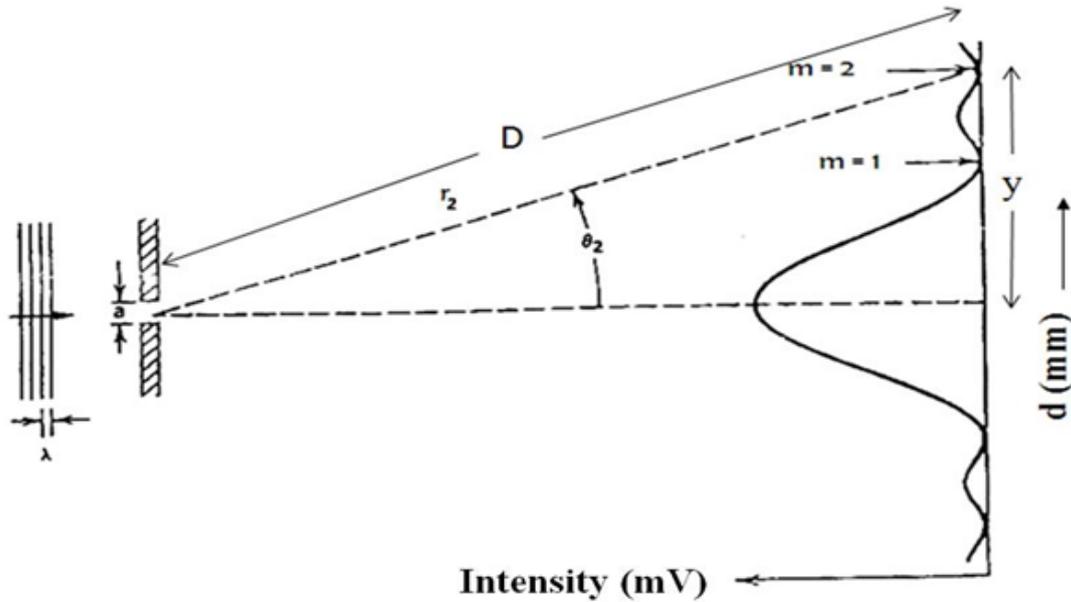


Figure 10.1: The Fraunhofer diffraction pattern of a single slit.

Fig. 10.1. If  $\theta_m$  is small, then

$$\sin \theta_m \approx \theta_m = \frac{m\lambda}{a}. \quad (10.3)$$

Further from geometry we have

$$\sin \theta_m \approx \theta_m = \frac{y}{D}. \quad (10.4)$$

where  $y =$  the distance between central maxima to the  $m$ th order minima point and  $D =$  distance between slit and photo diode (observed form instrument). Combining Eqs. 10.3 and 10.4, the slit width can be calculated as

$$a = \frac{m\lambda D}{y} \quad (10.5)$$

## Experimental procedure

1. Let the laser warm up for at least fifteen minutes before starting the experiment.
2. Position the laser at one end of the bench and align the beam so that it travels parallel to and along the central axis of the bench all along its length.
3. Let the beam pass through a beam expander. Adjust the slit position until the laser beam is incident on the full width of the slit.

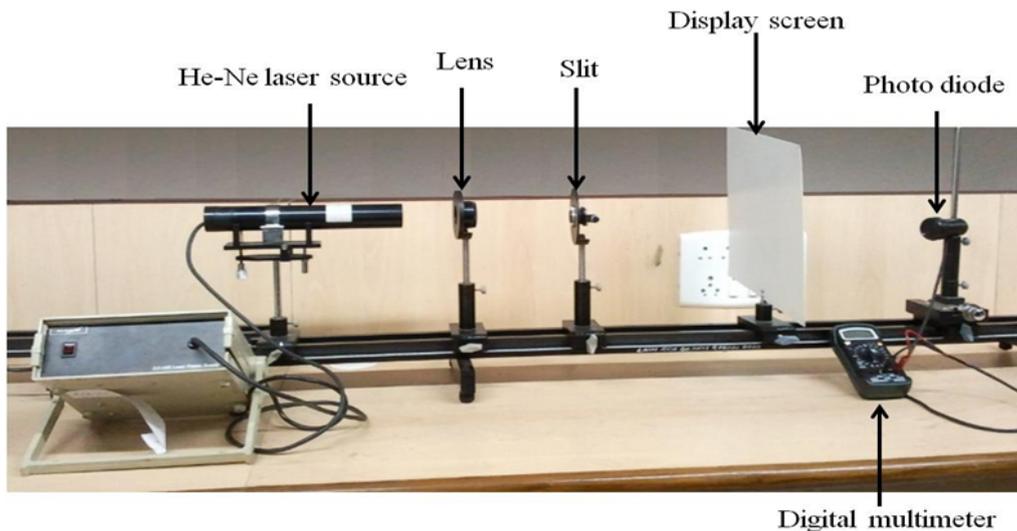


Figure 10.2: Experimental setup for single slit diffraction pattern

4. Attach the viewing screen to a component carrier and position it at the end of the bench furthest from the laser.
5. Observe the diffraction pattern on the screen. Adjust the screen position if necessary to obtain image clarity. Sketch the pattern observed for two different slit widths. What is the effect of varying the slit width?
6. Now replace the screen with the sliding detector. Beware that the smallest division on the sliding detector is 0.01 cm, and the detector can be moved over a distance of 4 cm. Check that the un-obstructed laser beam is at the proper level to be incident on the detector central slit-adjust if necessary.
7. Adjust the position of the slit along the optical bench until the central (principal) maximum and the first subsidiary maxima of the single slit diffraction pattern are fully extended along the direction of travel of the detector—obviously the pattern gets wider as the slit is moved closer to the laser and hence further away from the detector.
8. Form a clear diffraction pattern and SLOWLY scan the pattern from the central maxima to first maxima on the one side with the sliding detector for every 25 divisions of the circular scale.
9. Plot intensity versus position. How do your results agree with theoretical predictions?
10. Calculate the slit width using the diffraction Eq 10.5.

## Observation

Sl. No.	Distance			Intensity (mV)
	MSR (mm)	VSR	Total reading (mm)	
1.				
2.				
3.				
⋮	⋮	⋮	⋮	⋮

## Result

The calculated slit width from the diffraction pattern  $a = \dots\dots\dots$  mm.

## Precautions

1. Never look directly into the laser beam and take care to avoid reflections entering your eyes.
2. Do not disturb the setup once the diffraction pattern has been obtained.
3. Do not use the backlight of the multimeter. This would drain the battery of the multimeter.
4. Avoid stray light falling on the photo detector while measuring the intensity of light.

# Experiment 11

## Diffraction grating

### Purpose

- To understand the diffraction, diffraction grating and how diffraction grating works with the help of basic diffraction grating equations and experimental studies.
- To measure the wavelength of the light source with the help of diffraction grating.

### Apparatus

Spectrometer, diffraction grating, mercury light source, high voltage power supply, magnifying lens, spirit level, torch light, etc.

### Theory

#### Preliminary discussion

Interference refers to the interaction of two or more wave trains of light having the same frequency and having a phase difference which remains constant with time (coherent sources), so that they may combine with the result that the energy is not distributed uniformly in space but is a maximum at certain points and a minimum (perhaps zero) at others.

Diffraction phenomenon is described as the apparent bending of waves around small obstacles and the spreading out of waves past small openings. Diffraction patterns are marked by a rapid decrease in intensity with increasing distance from the center of the pattern.

A diffraction grating is made by making many parallel scratches on the surface of a flat piece of transparent material. It is possible to put a large number of scratches per centimeter on the material, e.g., the grating to be used has 6000 lines/cm on it. The scratches are opaque but the areas between the scratches can transmit light. Thus, a diffraction grating becomes a multitude of parallel slit sources when light falls upon it.

#### Diffraction grating equation

When parallel bundle of rays falls on the grating, these rays and their associated wave fronts form an orthogonal set so the wave fronts are perpendicular to the rays and parallel to the grating (as shown in Fig. 11.1). According to Huygens' Principle, every point on a wave front acts like a new source, each transparent slit becomes a new source so cylindrical wave fronts spread out from each. These wave fronts interfere either constructively or destructively depending on how the peaks and valleys of the waves are related.

Whenever the difference in path length between the light passing through different slits is an integral number of wavelengths of the incident light, the light from each of these slits

will be in phase, and then it will form an image at the specified location. Mathematically, the relation is simple

$$m\lambda = d \sin \theta_m \quad (11.1)$$

Eq. (11.1) is known as *grating equation*. The light that corresponds to direct transmission

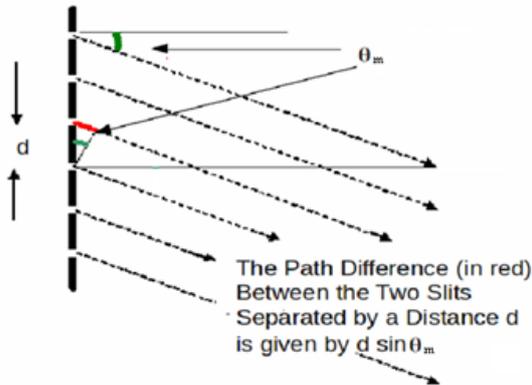


Figure 11.1: Geometrical conditions for the diffraction from multilayer grating.

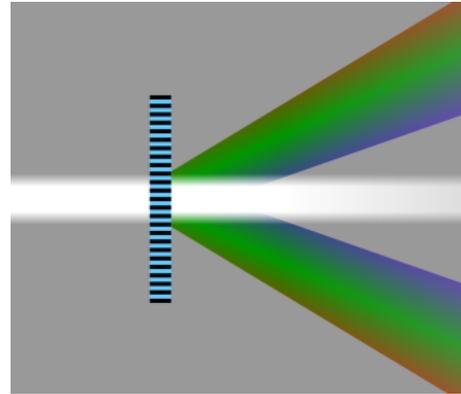


Figure 11.2: Spectrum due to a grating.

(or specular reflection in the case of a reflection grating) is called the zero order, and is denoted  $m = 0$ . The other maxima occur at angles which are represented by non-zero integers  $m$ . Note that  $m$  can be positive or negative, resulting in diffracted orders on both side of the zero order beam.

Diffraction gratings are often used in monochromators, spectrometers, lasers, wavelength division multiplexing devices, optical pulse compressing devices, and many other optical instruments.

### Resolving power of grating

This equation then leads to the following expression for the resolving power of the diffraction grating

$$R = \frac{\lambda}{\Delta\lambda} = mN \quad (11.2)$$

Here  $\lambda$  is the average of wavelength,  $\Delta\lambda$  is the difference between wavelengths,  $m$  is the order and  $N$  is the total number of slits on the grating.

Thus, the distance between maxima depends on the distance between slits and the resolution, the relative sharpness of the maxima, depends on the total number of slits. (Often a grating is characterized by the number of slits per unit length. From this information one can, of course, deduce the distance between the slits.

### Procedure

As with many optical instruments, the spectroscope requires some initial adjustments before the desired measurements can be performed. Focusing and levelling of the spectrometer for the parallel rays is to be done as per previous prism experiment.

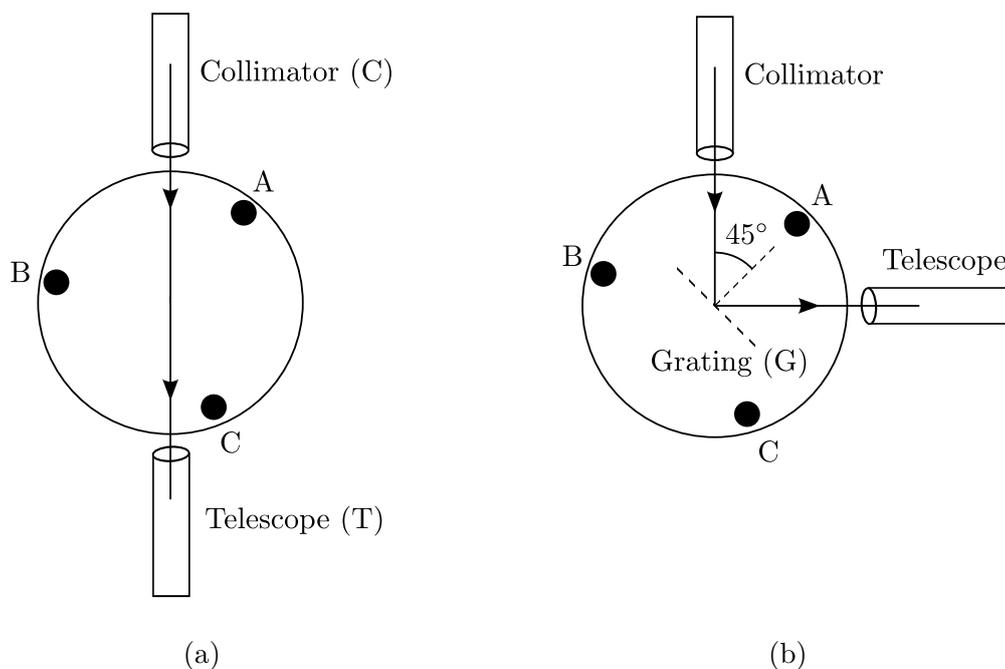


Figure 11.3: Grating settings

**To set the telescope axis perpendicular to that of the collimator:**

Illuminate the slit with the light source. Turn the telescope of the spectrometer to view the image of the illuminated slit directly as shown in Fig. 11.3(a). The source should directly be in front of the slit such that maximum light falls on the slit. Adjust the cross-wires such that the image of the slit falls in the middle of the intersection of the cross-wires. Fix the prism table with the fixing screw and read any of the two verniers. Let this angle be  $\alpha$ . Rotate the telescope by an amount  $90 \pm \alpha$  such that it is exactly perpendicular to the collimator. Fix the telescope in this position and unfix the prism table.

Fix the grating (G) in the grating holder such that the grating lines are perpendicular to the prism table and the ruled surface extend equally on both sides of the center. The grating is set parallel to the line joining the prism table screws B and C as shown in Fig. 11.3. Turn the prism table such that light from the collimator is reflected into the telescope. The reflection should be by the unruled surface of the grating. To determine the unruled surface use the following procedure. Allow light to be reflected by both the grating surface one at a time and view the corresponding image via the telescope. The surface from which the image of the slit appears sharper is in fact the unruled surface of the grating.

Once the unruled surface has been determined, view the reflection only via the unruled surface while the setup is as shown in Fig. 11.3(b). If the center of the grating displace either above or below the intersection of the cross-wires, then the grating surface is not vertical. To ensure that the grating surface is vertical, turn the prism table screws B and C equally in opposite directions until the center of the image coincides with the intersection of the cross-wires.

Turn the unruled surface of the grating by an angle  $45^\circ$  such that the light from the collimator falls normally on the unruled surface of the grating. Fix the prism table in this position and unfix the telescope.

Even though we have made the plane of the grating vertical and the rulings perpendicular to the table surface, the rulings of the grating may not be vertical. In order to set the rulings vertical, rotate the telescope in its own plane on both side of the central image. On both sides on the central image different orders of image are seen as shown in

Fig. 11.4. In the first order images on both sides, if the image on the left is higher than

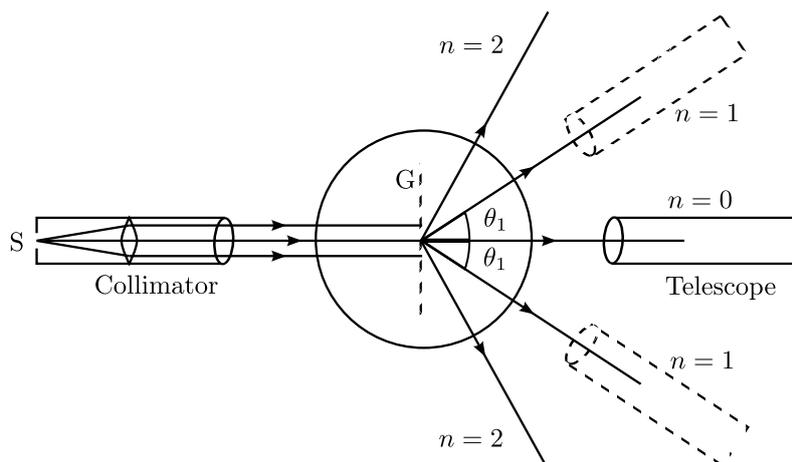


Figure 11.4: Grating images of higher order

that of the image on the right or vice-versa, then turn the third screw A on the prism table until the images on both the sides are on the same level.

### Caution

- The diffraction grating is a photographic reproduction and should NOT be touched. Make sure that the glassy base of grating shouldn't faces towards the source light.
- Now your setup is ready to report the experimental observations.

### Observation

1. Check to make sure that the grating is not too high or low relative to the collimator. Affirm maximum brightness for the straight through beam by adjusting the source slit alignment. At this step, the slit should be narrow, perhaps a few times wider than the hairline. Search for the spectrum by moving the telescope to one side or the other. This spectrum should look much like the visible spectrum observed with the prism. This is the first order spectrum. Record for each color diffraction angle  $\theta_R$  (along right side) and  $\theta_L$  (along left side) from the straight trough beam.
2. For each of the seven colors in the mercury spectrum, measure the angles  $\theta_R$  and  $\theta_L$  to the nearest tenth of a degree by placing the hairline on the stationary side of the slit.
3. You are expected to observe the 1<sup>st</sup> order diffraction pattern.
4. From your observations calculate various wavelengths of visible radiations from the mercury source.

### Calculation

1. Use the grating equation with  $d = (1/6000)$  cm to find the wavelength  $\lambda$  for each colour.
2. Calculate % error for your reported  $\lambda$  measurement.

Sl.	Colour	LHS			RHS			$2\theta = \theta_L - \theta_R$	$\theta$	$\lambda = \frac{d \sin \theta}{m=1}$
		CSR	VSR	Total ( $\theta_L$ )	CSR	VSR	Total ( $\theta_R$ )			
1	Violet									
2	Indigo									
3	Blue									
4	Green									
5	Yellow									
6	Orange									
7	Red									

Table 11.1: For first order ( $m = 1$ ). CSR - Circular scale reading, VSR - Vernier scale reading.

## Result

1. Percentage measurement error for your analysis.
2. A certain colour emerges at  $15^\circ$  in the first order spectrum. At what angle would this same colour emerge in the second order if the same source and grating are used?
3. What could be causing any discrepancy?
4. Why is it necessary that the base side of the grating face toward the light source? Draw a ray diagram for the two cases:
  - a) Base toward the source (correct).
  - b) Grating toward the source (incorrect).
5. Mention your special comments for each statement in your lab report as a part of experimental outputs.