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Indira Gandhi National Open University
School of Sciences

BPHCL-138
WAVES AND OPTICS: LABORATORY

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WAVES AND OPTICS: LABORATORY – INTRODUCTION

As you may be aware, physics is an experimental science which seeks to discover nature using the method of scientific enquiry. The vast body of knowledge we have about physical world has been supported by experimentation. That is why activities, demonstrations and experiments are integral components of science education.

In this laboratory course on Waves and Optics, you will be performing various experiments related to basic physics concepts you are learning in the theory course on Waves and Optics (BPHCT-137). We have included experiments in this course to give you a hands-on experience of working with a variety of optical components such as prism and diffraction grating and some common equipment such as spectrometer, telescope and travelling microscope. In addition, you will also learn to experimentally validate some of the concepts related to wave nature of light by taking careful measurements.

When you go to the laboratory to perform an experiment, you should have a clear idea about what you have to do and how you have to do it. Therefore, you are advised to read the write-up of each experiment carefully. You should familiarise yourself with the apparatus/equipment completely before performing the experiment.

In the study material for the course, we have given the introduction, expected skills to be learnt, basic theory and procedure for each experiment. The suggested layout for presenting your report for each experiment should consist of the following sections: aim, line or ray diagram, working formula, observation (tables), calculations, results and analysis/conclusions. You should correlate your results/findings with the standard values, wherever required.

The majority of the experiments in this course are related to optical phenomena such as refraction, polarisation, interference and diffraction. You have learnt the theoretical explanations of these phenomena on the basis of wave theory of light. These theoretical analysis have enabled scientists to come out with very precise measurement techniques for various physical quantities.

In Experiment 1, you will learn to use the simple phenomenon of refraction of light to determine the refractive index of the material of a prism. Polarimeter is equipment widely used in the pharmaceutical and chemical industry for precise determination of concentration of solutes in solutions. In Experiment 2, you will learn how this equipment works exploiting the phenomenon of polarisation of light. Experiment 3 is related to the dependence of the refractive index of a material on the wavelength of light passing through it. This dependence is expressed by Cauchy’s formula which says that every material has a unique set of constants called Cauchy’s constants. You will learn to determine these constants for the material of a prism.

Experiments 4 and 5 are related to the phenomenon of interference of light. While the former deals with interference due to division of wavefront, the later deals with interference due to division of amplitude. In Experiment 4, you will learn how to obtain two coherent sources of light using a combination of prisms called Fresnel biprism. You will also learn to set up experiment on an optical bench and take measurements using a micro-meter eye-piece. In Experiment 5, you will learn to produce interference fringe pattern in the form of rings called Newton’s rings and measure the fringe width to determine the wavelength of the light used.

Diffraction of light is a phenomenon which has helped develop many measurement techniques/ equipment. In view of its versatile utility, you will be performing quite a few experiments (Experiments 6, 9 and 10) related to this phenomenon. Diffraction grating is one such optical component which works on the principle of diffraction and it is used extensively in the field of spectral analysis. In Experiment 6, you will learn to use a diffraction grating to determine the wavelength of light. In Experiment 9 and 10, you will use some modern optical devices such as lasers and photo sensor to study the phenomenon of diffraction from an obstacle (wire) and an aperture (slit) respectively. The idea here is to give you an exposure to modern optical techniques which uses lasers and photo sensors for precise measurements. You should be mindful of the precautions one is supposed to take while using lasers.

The Experiments 7 and 8 deal with dispersion of light and resolving power of image forming devices, respectively. You will learn the skills of calculating these parameters by relating them to some measureable physical quantities.

As far as possible, you should work independently because your laboratory work will be evaluated continuously by your academic counsellor.

We hope you will have enjoyable experience working in the laboratory for this course.

We wish you good luck and success.

EXPERIMENT 1

REFRACTIVE INDEX OF THE MATERIAL OF A PRISM USING A SPECTROMETER

Structure

1.1 INTRODUCTION

In your school physics, you have studied reflection and refraction of light. When a ray of light is incident on a boundary separating two optically different media, a part of it is reflected at the boundary and the remaining part bends from its original path as it enters the second medium. The light is then said to have refracted. The extent of refraction is given by Snell's law and it is characterised by a parameter called **refractive index of the medium.** Higher the refractive index, greater is the bending of light.

In your +2 class physics, you must have studied several phenomena associated with refraction of light in everyday life. The rainbow in the sky is the most vivid example of refraction in nature. Similarly, appearances of an oasis in a desert and water on a coal tar road on a hot summer day are other familiar examples. You should list a few more examples of refraction and discuss with your counsellor.

A prism is a very useful and versatile optical device that is used in a variety of optical instruments such as binoculars, cameras, telescopes and submarine periscopes. A prism has a three-dimensional (3D) shape with two identical faces, which are called bases. In the physics laboratory, you will get a prism with equilateral triangular bases, though in the market polygon base prisms are also available. The other faces of a prism are rectangular. No dispersion or refraction takes place through the base as it is grounded.

The refractive index of the material of the prism plays an important role in the design and manufacturing of optical instruments. Newton showed that a prism disperses or breaks up white light into its seven constituent colours. Can you name these colours? [Remember, VIBGYOR (Violet, Indigo, Blue, Green, Yellow, Orange and Red).] The dispersion of light due to prism depends on the extent of refraction, which, in turn, depends on the wavelength of different colours constituting white light. It means that if we use a white light, the light emerging from a prism will show seven colours (wavelengths). However, in this experiment, we will use a sodium lamp, which is considered mono-chromatic (but, not strictly due to being a doublet of wavelengths 589.0 nm and 589.6 nm), and learn to determine the refractive index of the material of a given prism.

For determining the refractive index, we use a spectrometer to measure angles of dispersion, angle of minimum deviation of refracted rays and angle of the prism. A spectrometer is an optical instrument which enables us to observe spectrum of light given out by a source of light. However, in the present experiment, we shall make use of the spectrometer for measuring angles with high degree of precision.

Expected Skills

After performing this experiment, you should be able to:

- ❖ identify the refractive faces of a prism:
- ❖ identify the main components of a spectrometer;
- ❖ set up the spectrometer for experiment;
- ❖ determine the angle of the prism and angle of minimum deviation; and
- ❖ calculate the refractive index of the prism.

You will require the following apparatus for this experiment.

Apparatus Required

Spectrometer, prism, spirit level, sodium lamp and a reading lens (magnifying glass).

1.2 REFRACTIVE INDEX

The refractive index is a property of the material which determines the extent of refraction/bending of a ray of light passing through it. This parameter plays an important role in image formation by optical devices. From your school physics, you are familiar with the phenomenon of refraction of light and the concept of refractive index. But, for the sake of completeness, we briefly recall the basic concepts related to the refraction of light in the following paragraphs before you learn how to perform the experiment for determining the refractive index.

1.2.1 Refraction of Light

When light travels from one medium to the other, refraction of light refers to bending of a ray of light at the interface separating two optically different media. You may recall that when light travels from an optically rarer medium to an optically denser medium, it bends towards the normal. On the other hand, when light travels from an optically denser medium to an optically rarer medium, it bends away from the normal.

The two laws governing refraction of light are

i) The incident ray, the refracted ray and the normal at the point of incidence lie in the same plane.

ii) The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for any two media. This is also known as **Snell's law.**

Refer to Fig. 1.1. It shows a ray of light passing from medium *a* to medium *b* and if we denote the angle of incidence and angle of refraction by *i* and *r* respectively, then accordingly to **Snell's law,** we can write

$$\frac{\sin i}{\sin r} = \text{constant} \qquad (1.1)$$

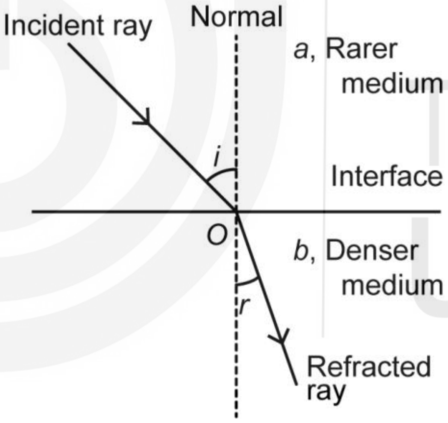


Fig. 1.1: **Refraction of light at the interface of two optically different media.**

The constant in Eq. (1.1) is referred to as the **refractive index of medium** *b* **with respect to medium** *a* and is denoted as

$$^{a}\mu_{b} = \frac{\sin i}{\sin r} \qquad (1.2)$$

If the first medium (the medium of incidence) is air, the refractive index of the second medium is simply denoted as μ. In this case, Eq. (1.2) is written as

$$\mu = \frac{\sin i}{\sin r} \qquad (1.3)$$

The value of μ for air is taken as unity.

Snell's law is an empirical law based on observations. The concept of refractive index was put on a sound theoretical foundation by Maxwell when he gave the theory of electromagnetic waves. According to this theory, the refractive index in a medium is given as the ratio of the velocity of light in vacuum and the velocity of light in that medium. Mathematically, we can write

$$\mu = \frac{\text{Velocity of light in vacuum}}{\text{Velocity of light in the specified medium}} \tag{1.4}$$

Snell's law is a natural consequence of Maxwell's electromagnetic theory. However, at present, we make use of the definition of the refractive index given in Eq. (1.1) because it is easier to measure the angles of incidence and refraction required to determine refractive index.

1.2.2 Refraction of Light through a Prism

A prism is a transparent wedge shaped structure (usually) made of glass with three rectangular and two triangular surfaces. The triangular faces are equilateral triangles and one of the rectangular surfaces is grounded.

A prism can be made from any material that is transparent for the light for which it has been designed. The materials, other than glass, used for making prisms are plastic and fluorite.

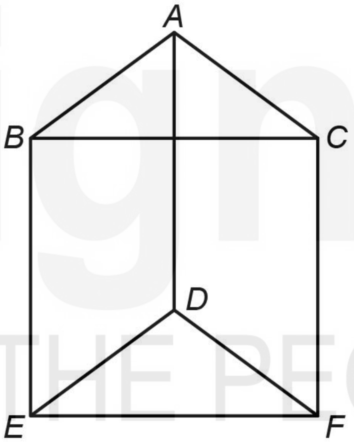


Fig. 1.2: **A Prism**

To understand the unique geometrical shape of a prism, refer to Fig. 1.2. The triangles *ABC* and *DEF* are equilateral triangles and are parallel to each other. Each of these triangular faces is called **base** of the prism. The side faces *ABED*, *ACFD* and *BCFE* of the prism are parallelograms and are called **sides** of the prism.

Though the most commonly used prisms in physics laboratory is triangular in shape, it can have a variety of shapes such as right angle prism (used in medical equipment, endoscope), penta prism (used in display systems), wedge prism (used in lasers), etc. depending upon the requirements.

Now, refer to Fig. 1.3 which shows the top view of the triangular prism *ABC*. The angle $\angle A$ is called **angle of prism**. A ray of light *PQ* incident on the face *AB* gets refracted along *QR* inside the prism. At *R* (located on the face *AC*), it again undergoes refraction and emerges out along *RS*.

Let *i* and *e* denote the angle of incidence and angle of emergence, respectively. The respective angles of refraction at *Q* and *R* are r_1 and r_2.

If *PQ* and *SR* are extended within the prism, they would meet at *G* (Fig. 1.3). The angle *HGS* ($\angle D$) is known as the **angle of deviation** and it is denoted by δ. Note that the angle of deviation is the angle through which the incident ray *PQ* has been deviated (refracted or bent) by the prism from its original direction *PQGH.*

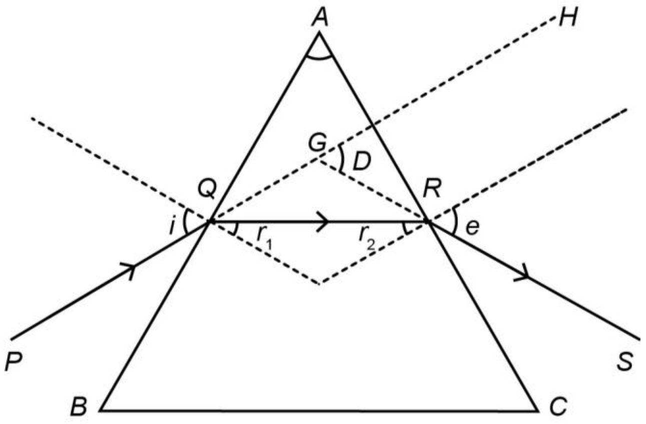


Fig. 1.3: **Refraction of light due to a prism.**

In order to determine the refractive index of prism material by any method using Snell's law [Eq. (1.3)], we need to measure the values of *i* and *r*. As such, measurement of the angle of refraction, *r* is practically difficult, so we look for some alternative method. An alternative and relatively easy method is by measuring a quantity called the **angle of minimum deviation**. Let us now learn what we mean by the angle of minimum deviation and how it helps in determining the refractive index of the prism material.

Minimum Deviation

For thick prisms, that is, a prism whose prism angle is relatively large (~ 60 degrees), the angle of deviation (δ) is large for small angle of incidence (*i*). As the value of *i* is gradually increased, the angle of deviation decreases progressively, till it reaches one particular value of angle of incidence, for which the *value of angle of deviation* becomes minimum. If the angle of incidence is increased beyond this value, the angle of deviation begins to increase. This angle for which deviation of the incident ray is minimum, is known as the **angle of minimum deviation** and it is denoted by δ_m.

When the angle of incidence is such that the angle of deviation has its minimum value, the incident ray passes through the prism symmetrically. That is, the refracted ray *QR* inside the prism becomes parallel to the base *BC* of the prism and $i = e$.

Before proceeding further, you should answer the following SAQ.

SAQ 1 - Angle of incidence and angle of emergence of a prism

Show that the angle of incidence and the angle of emergence of a prism are equal to each other when the angle of deviation is minimum.

Relation between Refractive Index, Angle of Prism and Angle of Minimum Deviation

To derive the relation between refractive index, angle of the prism and angle of minimum deviation, we note from Fig. 1.3:

$$i + e = A + \delta_m \tag{1.5}$$

and

$$A = r_1 + r_2 \tag{1.6}$$

SAQ 2 - Angle of minimum deviation of a prism

Using Fig. 1.3, establish the results contained in Eqs. (1.5) and (1.6).

Now, when the prism is in the position of minimum deviation, the refracted ray passes symmetrically through the prism and we can write from Fig. 1.3 that

$$i = e = i \tag{1.7}$$

and

$$r_1 = r_2 = r \tag{1.8}$$

Using Eq. (1.7) in Eq. (1.5), we can write

$$2i = A + \delta_m$$

$$\therefore \quad i = \frac{A + \delta_m}{2} \tag{1.9}$$

Further, using Eq. (1.8) in Eq. (1.6), we can write

$$A = r_1 + r_2 = 2r$$

or

$$r = \frac{A}{2} \tag{1.10}$$

From Eq. (1.3), we have

$$\mu = \frac{\sin i}{\sin r}$$

Substituting for *i* and *r* from Eqs. (1.9) and (1.10), we get the expression for refractive index in terms of easily measurable quantities (namely, angle of prism and angle of minimum deviation):

$$\mu = \frac{\sin \frac{A + \delta_m}{2}}{\sin(A/2)} \tag{1.11}$$

From Eq. (1.11), we note that we can easily determine the value of μ of the material of the given prism once we determine the values of the angle of the prism *A* and, the angle of minimum deviation δ_m.

To determine the value of *A* and δ_m, we use a prism spectrometer. So, we now discuss the construction and use of a basic laboratory spectrometer to make measurements.

1.3 SPECTROMETER

Spectrometer is an optical instrument used to study the spectra of different sources of light and to determine the refractive indices of materials. A typical laboratory spectrometer is shown in Fig. 1.4.

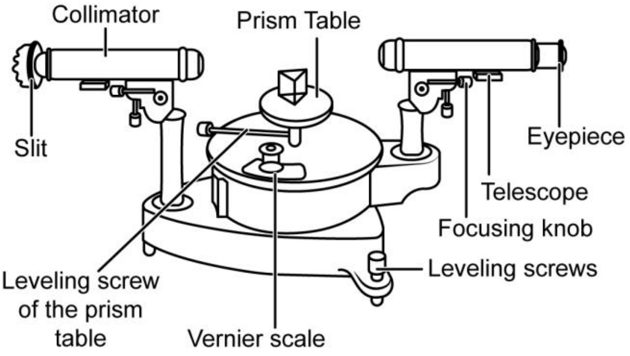


Fig. 1.4: **A typical laboratory spectrometer.**

1.3.1 Parts of a Spectrometer

A spectrometer consists of three main parts: (i) A collimator, (ii) a telescope and (iii) a prism table. We now discuss their construction and working.

i) Collimator

The collimator is a device used to produce a parallel beam of light. It consists of a long cylindrical tube having a vertical slit *S* of adjustable length and width at the outer end and a convex lens at the inner end of the tube. The distance between the slit and the lens can be so adjusted that the slit is at the focus of the lens. Then the length of the tube becomes equal to the focal length of the lens of the collimator. The slit is so kept that it faces the source of light. The collimator is rigidly fixed to the base of the spectrometer.

ii) Telescope

The telescope in a spectrometer is a simple astronomical type telescope with an eye piece of Ramsden type provided with cross wires at one end of the tube and an objective lens at the other end placed coaxially. The distance between the objective lens and the eyepiece can be adjusted using screw to obtain a clear image at the cross wires when a parallel beam of light coming out of the collimator is incident on the objective of the telescope. The telescope can rotate about the same vertical axis as the prism table. The telescope is also provided with radial screws for fixing it in the desired position.

The eye piece of an optical instrument is a simple magnifier. However, a single lens is inadequate as it gives rise to aberration. In Ramsden eye piece, two plano-convex lenses made of same material and having same focal length are used to minimise aberration effects.

The base of the telescope is fitted with two vernier scales, which move over a circular graduated main scale. This arrangement enables us to measure the angle of rotation of the telescope very accurately.

iii) Prism Table

The prism table is a circular table of adjustable height and can rotate about the same vertical axis as the telescope. The prism table carries three screws at its bottom. These are used to level it. The prism table is provided with a vertical stand so that it can be moved up or down. The prism is placed on the table such that its refracting surfaces are perpendicular to the plane of the table.

To summarise, light enters the collimator through an adjustable slit and the collimating lens produces a parallel beam of light, which is then made to pass through a prism (or diffraction grating) placed on the prism table. On passing through the prism (or grating), the light bends through some angle and is then viewed through the telescope that can be moved about a vertical axis. The angle through which light bends can be very accurately measured using a vernier scale, which moves on a circular graduated main scale attached to the telescope.

Before using a spectrometer for measurements, certain adjustments have to be made. A proper setting up of the spectrometer is very important for accurate measurement in an experiment with spectrometer. You must master it for obtaining accurate results. We now discuss how to set up a spectrometer, step by step.

1.3.2 Setting up the Spectrometer

The basic objective of setting up the spectrometer for experiment is to align its different components with each other. The light beam emerging from the prism should be incident on the telescope objective in such a manner that a clear image is formed on the cross wires of the telescope. The adjustments required before working with a spectrometer are:

i) the axis of the spectrometer is to be made vertical so that it coincides with the vertical axis of rotation of the prism table;

ii) the axes of the collimator and the telescope should be horizontal so that they are perpendicular to the axis of the prism table;

iii) the refracting faces of the prism should be vertical so that these are parallel to the axis of rotation of the telescope; and

iv) the collimator and the telescope should be adjusted for parallel rays.

While working with spectrometer, you should keep in mind that all adjustable parts of the spectrometer should move with very little effort; do not force any part of the spectrometer for movement. If you move a part by force, you may deform it or even break it. Some parts can probably be tight as it may be clamped. In such a situation, check it and locate the appropriate knob to loosen it.

The procedure to adjust different components of the spectrometer is as follows:

i) *Levelling:* To level the telescope, take a spirit level and keep it on the telescope tube along its length. Use the screws provided at the base of the spectrometer to bring the bubble of the spirit level at the centre. Rotate the telescope tube by 180 degrees and again use the base screws to bring the bubble at the centre. Repeat this process until the spirit level bubble remains at the centre for different positions of the telescope. This levelling ensures that the telescope is perpendicular to the vertical axis of the prism table. Similarly, you can level the collimator tube using the spirit level and the screws provided with the collimator tube. Further, to level the prism table, you can use one of the following two methods:

   a) Prism table can be levelled using a spirit level. Place the spirit level at the centre of the prism table and bring the bubble of the spirit level at the centre by adjusting the screws provided at the bottom of the prism table. Change the position of the spirit level on the prism table and again, use the prism table screws to bring the bubble at the centre. Repeat this process for different positions of the spirit level on the prism table. By this adjustment, you have made the prism table horizontal. Thus, when you place the prism on this table, its refracting surfaces will be perfectly vertical, that is, they will be perpendicular to the collimator and telescope axes.

   b) Sometimes, the levelling of the prism table by spirit level is not sufficient. In such a situation, the prism table should be levelled optically. This consists of the following steps:

- Illuminate the collimator slit by sodium light. (Do you know the mechanism of emission of light by a sodium lamp? Discuss with fellow students as well as with your academic counsellor, if you are not able to get correct reference.) Place the prism at the centre of the prism table such that one of its faces *AB* is perpendicular to the line joining the two screws P_1 and P_2 (Fig. 1.5).

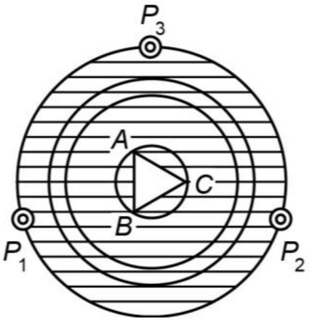


Fig. 1.5: **Prism on a prism table.**

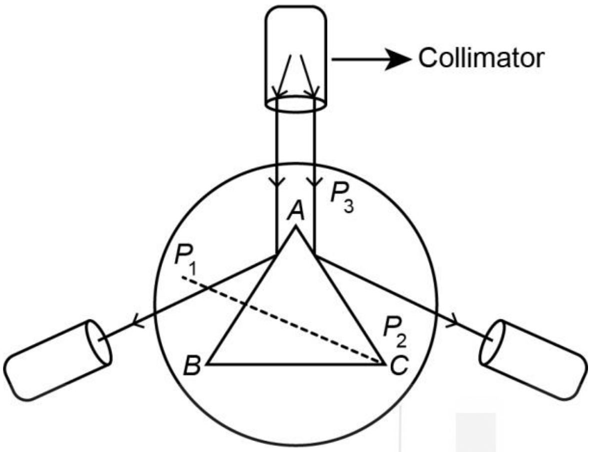


Fig. 1.6: **Optical levelling of prism table.**

- Rotate the prism table so that the refracting edge points towards the collimator and light falls on both the refracting surfaces of the prism, as shown in Fig. 1.6.

- Turn the telescope till you see the image of the slit due to light reflected from the *AB* side of the prism. Is the image symmetrical with respect to the horizontal cross wire of the telescope? If not, adjust the screws P_1 and P_2 by moving them in opposite directions so that the image is exactly at the centre of the field of view of the telescope.

- Next, rotate the telescope to see the image of the slit due to light reflected from side *AC* (Fig. 1.6). Again ensure that the image is symmetrical with respect to the horizontal cross-wire of the telescope. If not, adjust the screw P_3. Turn back the telescope towards face *AB* and repeat the earlier process, if the symmetry has been disturbed.

- Repeat the process till the slit image is symmetrical with respect to horizontal cross-wire in both the positions of the telescope.

With these adjustments, you have made the collimator, telescope and the prism table horizontal and perpendicular to the vertical axis of the prism table.

ii) *Focussing the cross-wire:* Keep the telescope objective towards any illuminated background and move the eye piece inward or outward until you see the cross wires more clearly.

iii) *Adjustment of the slit:* Remove the prism from the prism table and place the telescope in line with the collimator and see through the eye-piece of the telescope. Obtain a sharp image of the (collimator) slit by turning the focussing screw of the telescope and of the collimator. The slit can be made vertical by turning it in its plane and its width should be adjusted to about 1 mm using the attached screw. (The slit should be narrow.)

iv) *Adjusting the collimator and the telescope for parallel rays:* The telescope and collimator can be focussed for parallel rays in two ways:

a) Take the spectrometer out of the dark room and focus the telescope on a distant object like a tree or a street light and obtain the best distinct image of the object by adjusting the focussing screw.

b) By Schuster's method: This is a better and more scientific method for focussing the telescope and collimator for parallel rays. It involves the following steps:

- Illuminate the collimator slit with sodium light. Bring the telescope in line with the collimator and adjust the slit and levelling screws of the apparatus so as to obtain the image of the slit at the centre of the field of view of the telescope.
- Adjust the telescope by rotating it so that vertical cross-wire coincides with the slit. Adjust the eye-piece so that the cross wires are distinctly visible.
- Place the prism on the table and adjust its height to receive collimated light beam on one of its refracting surfaces. If you look through the other refracting surface of the prism and by moving towards its base, you will see the image of the slit through the prism by unaided eye.
- Now, rotate the prism table in such a direction that the image of the slit approaches the direct path of the rays from the collimator.
- Bring the telescope to this position of the image. This is the approximate position of minimum deviation which is indicated by the fact that around this position, the slit image moves to only one side (away from the direct path from collimator) in the field of view of telescope irrespective of the direction of rotation of the prism table, clockwise or anti-clockwise. Fix the telescope in this position (Fig. 1.7).
- Now rotate the prism table slightly so that the angle of incidence on its refracting surface is greater than that corresponding to the minimum deviation position (Fig. 1.7). Focus the telescope using the adjustment of its eye piece till the slit image is sharp.
- Rotate the prism table in the opposite direction so that the angle of incidence is slightly less than that corresponding to minimum deviation position (Fig. 1.7). Focus the collimator by turning the screw attached with it and get a sharp image of the slit.

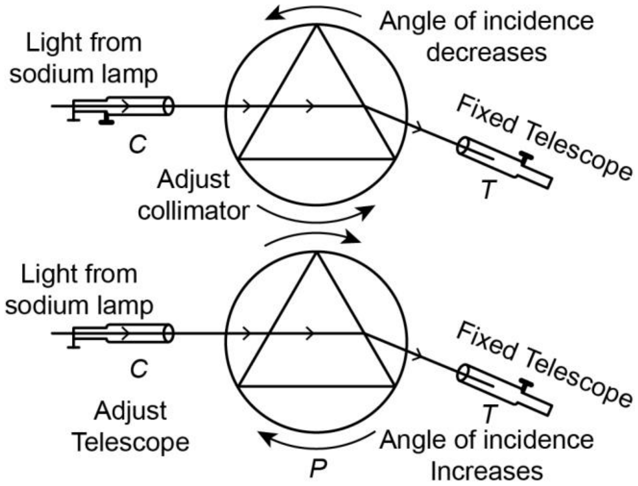


Fig. 1.7: **Schuster's method for focussing telescope and collimator for parallel rays.**

- Now again turn the prism in opposite direction to come back to initial position (angle of incidence greater than that for minimum deviation). The image of the slit gets blurred. Focus the image by adjusting the screw of the telescope to get the sharp image.
- By repeating these two steps a few times, a sharp image of the slit in both positions of the prism will be obtained. This ensures focussing of collimator and telescope for parallel rays.
- In order to avoid confusion, remember that, when the refracting edge of the prism is nearer to you (observer), the image is focussed by the telescope (which is nearer to you) and when the refracting edge of the prism is farther from you, the image is focussed by the collimator (which is farther from you).
- If these steps are not followed in order, the image will worsen instead of improving.

Source of Light

The source of light used in an experiment is decided by the objective of the experiment. For example, if we have to determine wavelengths of various colours of light obtained due to dispersion, we use a mercury lamp. However, to determine the refractive index of the material of a prism using a spectrometer, we need a monochromatic source of light. The sodium vapour lamp is commonly used as a monochromatic source. However, the fact is that this source emits a doublet of wavelengths 589.0 nm and 589.6 nm. Since the difference in the wavelengths is extremely small, it is taken as a monochromatic source for all practical purposes and the wavelength of emitted light is taken as 589.3 nm, the average of the two.

1.4 EXPERIMENTAL PROCEDURE

First of all, you should set up the spectrometer as described in the previous section. This is a necessary requirement for making any measurement with it.

1.4.1 Vernier Constant of the Spectrometer

As mentioned earlier, a spectrometer has two circular vernier scales attached to its base which enables us to determine the angle by which the telescope has been rotated. You are familiar with the concept of vernier scale and vernier constant or least count from your school physics. You also got an opportunity to calculate the least count of a vernier in the first semester laboratory course entitled 'Mechanics: Laboratory' (BPHCL 132). You know that the difference between the value of one main scale division (MSD) and one vernier scale division (VSD) is called the vernier constant or the **least count** (LC) of the instrument and it is the smallest measurement that can be done accurately using a vernier scale.

In case of spectrometer, the circular verniers are used to measure angles up to accuracy in minute. In ordinary laboratory spectrometers, each main scale division is equal to half a degree and the vernier scale is such that 30 VSD coincide with 29 MSD. (You must verify that it is true for the spectrometer with which you are doing the experiment.) Thus, we write

$$1\,\text{VSD} = \frac{29}{30}\,\text{MSD}$$

So,

Least Count = $1\text{MSD} - 1\,\text{VSD}$

$$= 1\ \text{MSD} - \frac{29}{30}\text{MSD} = \left(1 - \frac{29}{30}\right)\text{MSD} = \frac{1}{30}\text{MSD}$$

Now

$$1\ \text{MSD} = \frac{1}{2}^{\circ} = 30'$$

$$\therefore \qquad \text{LC} = \frac{1}{30} \times \left(\frac{1}{2}\right)^{\circ} = \left(\frac{1}{60}\right)^{\circ} = 1'$$

In some spectrometers, 40 VSD may coincide with 39 MSD and accordingly, the LC for such spectrometers will have different value. So, you must check the spectrometer vernier scale before calculating its LC.

Working Formula

For determining the refractive index of the material of the prism, you will use the formula given by Eq. (1.11):

$$\mu = \frac{\sin\dfrac{A+\delta_m}{2}}{\sin A/2}$$

where, A is angle of prism and δ_m is angle of minimum deviation.

So, we need to measure the values of A and δ_m. The procedure for these measurements is given below.

1.4.2 Measurement of the Angle of Prism

i) Switch on the sodium vapour lamp.

ii) Set up the spectrometer following the procedure explained in Sec. 1.3.2.

iii) Place the prism on the prism table with its refracting edge *AB* and *AC* faces the collimator as shown in Fig. 1.8. In this position, the parallel beam of light coming from the collimator will fall on the refracting surfaces of the prism. You must note that the slit is visible from both the faces with unaided eye.

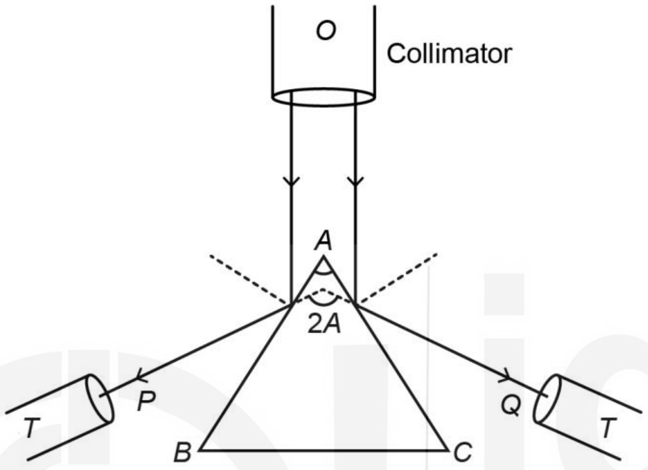


Fig. 1.8: **Set up for measuring the angle of prism.**

iv) Move the telescope to a position, say *P*, so as to receive light after reflection from face *AB* and you can see the image of the slit.

v) Adjust the vertical cross-wire of the eye piece so that it coincides with the slit image.

vi) Note the reading of main scale and vernier scale on both the vernier windows V_1 and V_2 in the Observation Table 1.1.

vii) Now, move the telescope and bring it to a position, say *Q* (Fig. 1.8) so as to receive light after reflection from face *AC* of the prism and you can see the image of the slit.

viii) Note the reading of main scale and vernier scale on both the vernier windows V_1 and V_2 in the Observation Table 1.1.

ix) Take three independent set of readings for telescope positions at *P* and *Q* each.

x) The angle between these two positions gives 2*A*, twice the angle of the prism. Calculate the mean value of *A*.

For measuring angles of prism, the prism table should be set in such a position so that the reading in V_1 has small initial value, say between 0° and 0° . By doing so, you ensure that, after turning the telescope towards other face, an addition of 120° (usually A ~ 60°) will not exceed 150° and correspondingly the reading on V_2 will not exceed 360°. This avoids the confusion while taking the difference of two readings.

1.4.3 Measurement of the Angle of Minimum Deviation

The steps to set-up the experimental arrangement to measure the angle of minimum deviation are given below:

i) Place the prism on the prism table with one of its refracting surface *AB* facing the collimator and the centre of the prism coinciding with the centre of the table as shown in Fig. 1.9.

ii) Look through the other refracting surface *AC* of the prism to see the image of the slit, formed due to refraction of light, with unaided eye.

iii) Rotate the prism table slowly in such a direction that the image seen by the unaided eye moves as close as possible to the direct ray from the collimator (shown by the dotted line *CD* in Fig. 1.9). If you continue rotating the prism table slowly in the same direction further, you will observe that, at some point, the image will begin to move away from the direction of the direct ray from the collimator. The position of the prism where the image just begins to move away from the direct ray is the approximate position of the prism for minimum deviation.

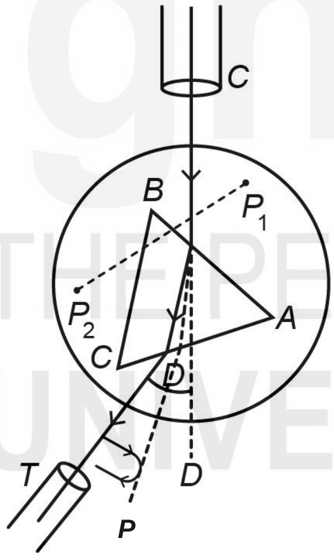


Fig. 1.9: **Set up for measuring the angle of minimum deviation.**

iv) Bring the telescope to this position (position *P* in Fig. 1.9). Adjust the vertical cross-wire of the eye piece so as to coincide with the image of the slit.

v) For fine tune the position of minimum deviation, rotate the prism table **slightly** with the help of tangent screw so that the image moves in the direction of decreasing deviation (that is, closer to the direct ray).

vi) Rotate the telescope using the tangent screw to align its cross-wire with the new position of the slit image. This is the precise position of the prism for minimum deviation.

vii) Continue with these slow adjustments of the prism table and the telescope till the slit image just begins to move in the opposite direction (that is, moves in the direction of increasing deviation).

viii) Note down both the vernier readings in the Observation Table 1.2.

ix) Now remove the prism from the prism table. Align the telescope with the direct ray from the collimator so as to see the image of the slit. Adjust the vertical cross-wire of the eye piece with the slit image.

x) Note the vernier readings for this position of the telescope in the Observation Table 1.2. This is the **direct ray reading**.

xi) The difference between the mean readings for the minimum deviated ray and the direct ray gives the angle of minimum deviation δ_m of the prism.

xii) Take two sets of readings for δ_m and calculate the mean value of δ_m.

Keep either telescope or the prism table clamped while adjusting the other for proper readings.

Observations:

Least Count (LC) of the vernier of spectrometer = ...

Wavelength of the light used (Na-light) = 589.3 nm

Observation Table 1.1: Angle of Prism, *A*

No. of Observation	Vernier	1st Position of Telescope (X)			2nd Position of Telescope (Y)			Difference ($Y - X$) (=$2A$)	Angle of Prism A
		MSR	VSR	Total	MSR	VSR	Total		
1	V_1								
	V_2								
2	V_1								
	V_2								

Note that you need to multiply the vernier scale reading (VSR) by vernier constant or least count (LC) of the vernier before adding it to the main scale reading (MSR) to get Total (X or Y).

Mean A = ...

Observation Table 1.2: Angle of Minimum Deviation, δ_m

No. of Observ-ations	**Vernier**	**Minimum Deviation Ray (X)**			**Direct Ray (Y)**			**Difference, ($Y-X$) $=\delta_m$**
		MSR	**VSR**	**Total**	**MSR**	**VSR**	**Total**	
1	V_1							
	V_2							
2	V_1							
	V_2							

Mean δ_m = ...

1.4.4 Calculations and Result

You can calculate the refractive index of the material of the prism by substituting the values of A and δ_m in Eq. (1.11):

$$\mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\frac{A}{2}}$$

Refractive index of the medium of the prism for sodium light =..............

$$\text{Percentage error} = \frac{\text{Experimental value} - \text{Standard value}}{\text{Standard value}} \times 100$$

$$= \qquad \%$$

Discuss your result with your academic counsellor.

EXPERIMENT 2

INVESTIGATIONS WITH POLARISED LIGHT USING A POLARIMETER

Structure

2.1 INTRODUCTION

You are familiar with various kinds of rotations. You must have observed rotating blades of a fan, a spinning top and merry-go-rounds in motion. The Earth rotates around its axis. You have also read about artificial satellites that rotate about their axis while orbiting around the Earth. All these are examples of rotations of specific physical objects. In physics, we also need to visualise rotations of different other kinds to understand some useful concepts and important phenomena. In Unit 5 of the course entitled Waves and Optics (BPHCT-137), we explained the phenomenon of polarisation of light with the help of a polariser and an analyser and the rotation of the analyser with respect to the polariser.

In your school physics, you have learnt that polarisation is peculiar only to transverse waves. You also learnt in Unit 5 of BPHCT-137 course that the electric (or, equivalently, magnetic) field vectors associated with a linearly polarised light vibrate in a fixed plane which is perpendicular to the direction of propagation of the light.

The study of polarisation of light is a useful tool for several scientific investigations. For example, the study of interaction of polarised light with material substances provides valuable information about their optical properties. It has been observed that, when a linearly polarised light passes through certain substances, the orientation of the plane of polarisation of light changes.

Such substances are called **optically active** substances. A few optically active substances produce clockwise rotation of the plane of polarisation while some others produce counter clockwise rotation. The extent of rotation of the plane of polarisation and the direction of rotation enable us to identify the substance and also determine the concentration of the substance in a solution.

In this experiment, you will learn to determine the angle by which the plane of polarisation of a linearly polarised light rotates when it passes through a solution of an optically active substance. You will also learn how to calculate the concentration of the solute in the solution using the angle of rotation.

To measure the rotation of the plane of polarisation of light, we use **polarimeter**. It can also be used for pharmaceutical analysis to determine concentration of various constituents of drugs. But in a physics laboratory, we will use it to determine the concentration of sugar in a solution by studying the rotation of the plane of polarisation of light. This method is known as **polarimetry**.

Expected Skills

After performing this experiment, you should be able to:

- identify different components of a polarimeter;
- identify the tint of passage of light;
- establish the relation between concentration of solution and angle of rotation of the plane of polarisation;
- measure the rotation of plane of polarisation; and
- determine the concentration of a given solution.

You will require the following apparatus for this experiment.

Apparatus Required

Polarimeter, measuring flask, physical balance, sugar and distilled water.

2.2 POLARISATION AND OPTICAL ACTIVITY

In Units 4 and 5 of the course entitled Waves and Optics (BPHCT-137), you have learnt about electromagnetic waves and polarisation of light, respectively. You now know that electromagnetic waves are transverse in nature. In fact, polarisation of light is a strong experimental evidence supporting the transverse nature of light (and electromagnetic waves).

From Unit 5 of BPHCT-137, you may recall that the electric (as well as the magnetic) field vectors associated with an unpolarised light wave propagating in the z-direction can be represented by vectors in the xy-plane (Fig 2.1a). Note that the electric (as well as magnetic) field vectors of an unpolarised light can have all possible orientations in the xy-plane.

To simplify this representation of the unpolarised light, we resolve electric field vector $\vec{\mathbf{E}}$ into its components, say $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$ along the *x*- and *y*-axes, respectively, as shown in Fig. 2.1b. Note that when we allow all orientations for the electric field vector in the *xy*-plane and resolve each one of them along the *x*- and *y*-axes, we include the contribution of all electric field vectors of the unpolarised light in $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$. So, the net result is that we can represent unpolarised light in terms of two mutually perpendicular electric field vector components $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$. Note that $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$ are actually the resultant of a large number of components associated with individual electric field vectors representing the unpolarised light (Fig. 2.1a). Also note that each of these components are plane (or, linearly) polarised because each one of these is confined to a plane containing *z*-axis and the plane has fixed orientation.

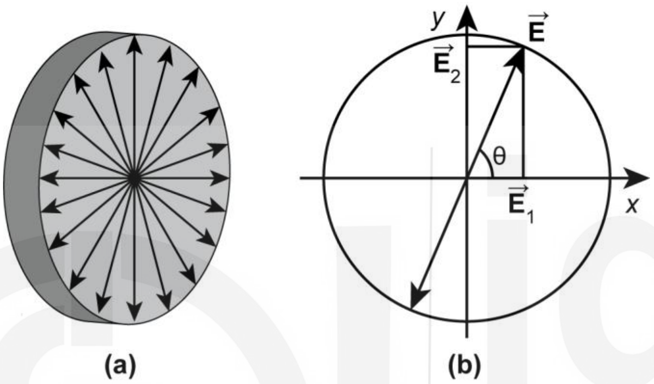


Fig. 2.1: **a) Electric field vectors associated with an unpolarised light propagating along *z*-direction; b) Resolution of an electric field vector of the unpolarised light into its components.**

The pictorial representation of the unpolarised light as per the simplified scheme described above is shown in Fig. 2.2. Fig 2.2a and 2.2b show two plane (or, linearly) polarised components (one along the *x*-axis and the other along the *y*-axis) $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$ for a beam of unpolarised light propagating along the *z*-axis. Fig 2.2c shows two orthogonal vibrations together: the arrows represent vibrations in the plane of the paper and dots represent the vibrations perpendicular to the plane of the paper.

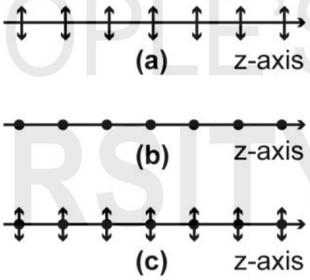


Fig. 2.2: **Electric field vibrations a) in the plane of the paper; b) perpendicular to the plane of the paper; c) the two orthogonal electric vibrations, representing an unpolarised beam of light, shown together.**

Mathematically, the components of electric field $\vec{\mathbf{E}}$ of a monochromatic light of frequency ω, propagating along the positive *z*-axis, are written as

$$\vec{\mathbf{E}}_1(z,t) = E_{10}\,\hat{\mathbf{i}}\sin(kz-\omega t) \tag{2.1}$$

$$\vec{\mathbf{E}}_2(z,t) = E_{20}\,\hat{\mathbf{j}}\sin(kz-\omega t+\phi) \tag{2.2}$$

where $k(=2\pi/\lambda)$ is the wave number, $\omega(=2\pi f)$ is the angular frequency, $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$ are unit vectors along *x*- and *y*-axes, respectively, *f* is the frequency and ϕ denotes the phase difference.

As is evident from Fig. 2.1a, the electric field vectors associated with a beam of unpolarised light, say from the sun or incandescent lamp, propagating along the *z*-axis can have random orientation in the *xy*-plane. This implies that the phase difference between the components of the electric fields fluctuates **randomly**. On the other hand, for a beam of plane polarised light, the direction of vibration of the electric field vector remains fixed in the *xy*-plane and the phase difference between its components is constant. Further, you may also recall from Unit 5 of BPHCT 137 that, depending on the value of the phase difference and the relation between the amplitudes of $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$, the following **states of polarisation** of light are possible due to the superposition of $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$:

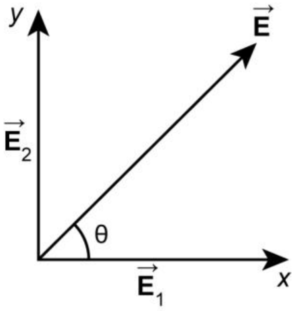


Fig. 2.3: **Linearly or plane polarised light.**

a) When the phase difference, ϕ is zero, $\vec{\mathbf{E}}_1$ and $\vec{\mathbf{E}}_2$ are in phase and the resultant $\vec{\mathbf{E}}$ field vector oscillates along a line that makes an angle, say, θ with the *x*-axes, as shown in Fig. 2.3. Such a beam of light is said to be **linearly or plane polarised**.

The angle θ is given by

$$\theta = \tan^{-1}\frac{E_{20}}{E_{10}} \tag{2.3}$$

b) When the phase difference, $\phi = \pi/2$ and $E_{10} = E_{20}$, Eqs. (2.1) and (2.2) take the form

$$\vec{\mathbf{E}}_1(z,t) = E_{10}\,\hat{\mathbf{i}}\sin(kz - \omega t) \tag{2.4}$$

$$\vec{\mathbf{E}}_2(z,t) = E_{10}\,\hat{\mathbf{j}}\cos(kz - \omega t) \tag{2.5}$$

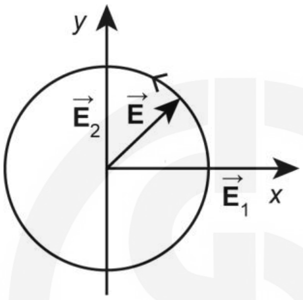
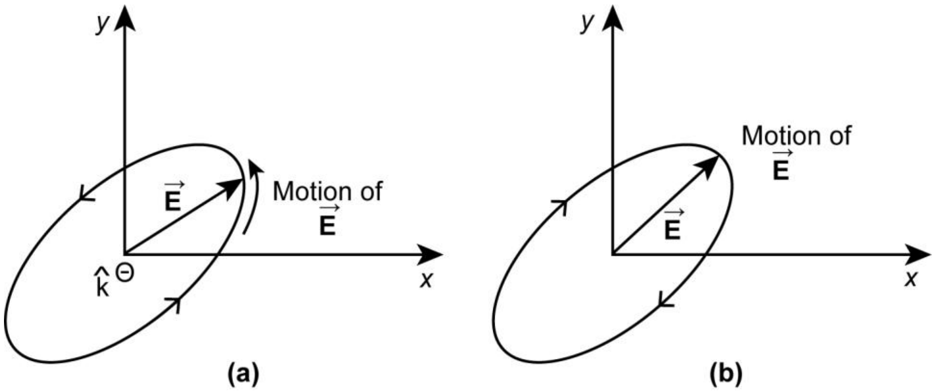


Fig. 2.4: **Circularly polarised light.**

In this case, the tip of the resultant electric field $\vec{\mathbf{E}}$ moves along a circle in the plane of the page as shown in Fig. 2.4. Such a polarised light is called **circularly polarised light**. Since there can be two senses of rotation of the tip of electric field vector, there are two distinct states of circular polarisation. By convention, if we look in the direction of propagation of the beam coming out of the plane of paper and observe that the tip of the electric field rotates in the anti-clockwise direction, then the light is said to be **left circularly polarised**. And, if the tip of $\vec{\mathbf{E}}$ rotates in the clockwise direction, the light is said to be **right circularly polarised.**

c) When the phase difference, $\phi \neq m\pi/2$ (m = 0, 1, 2, 3, ...) and $E_{10} \neq E_{20}$, the tip of the resultant electric field vector moves along the circumference of an ellipse as shown in Fig. 2.5. Again, as in the case of circular polarisation, two senses of rotation are possible for elliptically polarised light. Thus, we have right elliptically polarised and left elliptically polarised lights (Fig. 2.5).



(a) (b)

Fig. 2.5: **a) Right elliptically polarised light; b) Left elliptically polarised light.**

You may recall from Unit 5 of BPHCT-137 that linear and circular polarisations are special cases of elliptical polarisation; when *m* becomes even and odd multiples of $\pi/2$, the elliptically polarised light reduces respectively to linearly polarised light and circularly polarised light.

Now that you know the basics of polarisation and the states of polarisation, let us learn about optical activity.

Optical Activity

There are several solids, liquids and their solutions which cause rotation of the plane of polarisation of linearly polarised light when it passes through them. Such materials are called **optically active** materials. This property of materials was first discovered by French physicist Dominique F.J. Arago when he observed that the plane of polarisation of linearly polarised light changed continuously as it propagated along the optic axis of a quartz plate. This is shown in Fig. 2.6. (At about the same time, Jean B. Biot also observed this phenomenon while using the vapour and liquid forms of turpentine.)

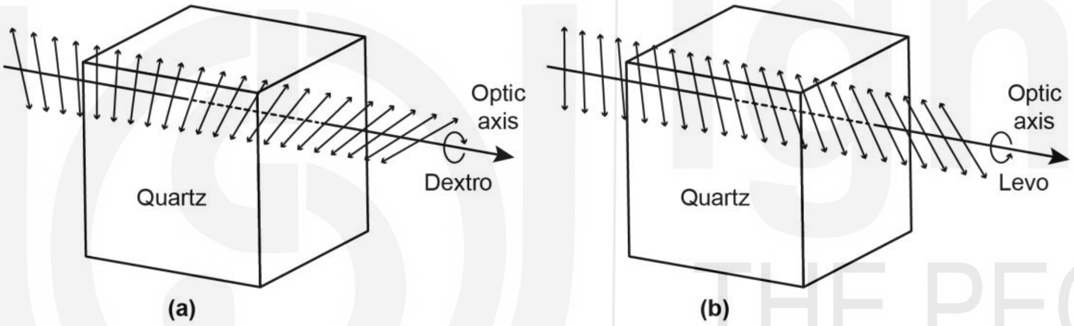


Fig. 2.6: **Rotation of the plane of polarisation of a linearly polarised light in an optically active medium: a) dextrorotatory medium; b) levorotatory medium.**

Further, it has been observed that rotation of the plane of polarisation can be either clockwise (that is, right handed) or anti-clockwise (that is, left-handed) depending on the material under investigation. If we look into the incoming beam and observe that the plane of polarisation has rotated clockwise, the substance is referred to as **dextrorotatory** or *d*-**rotatory** (Fig. 2.6a). On the other hand, if the plane of polarisation rotates anti-clockwise, the material is called **levorotatory** or *l*-**rotatory** (Fig. 2.6b).

You must have studied that a quartz crystal shows both *d*-rotatory and *l*-rotatory behaviour. Although all constituent molecules of quartz (SiO_2) are identical, a quartz crystal can be *d*-rotatory as well as *l*-rotatory, depending upon the arrangement of these molecules (that is, its crystallographic structure). Therefore, the type of rotation produced by a crystalline substance is intimately related to its molecular structure. (Molten quartz and fused quartz are not optically active. Can you guess why it is so? This is because these forms of quartz are non-crystalline.)

There are many other substances, both organic as well as inorganic (such as benzyl and $NaBrO_3$), which, like quartz, exhibit optical activity in crystalline form. In contrast, many naturally occurring organic compounds such as sugar, tartaric acid and turpentine, are optically active in solution or in the liquid state. The extent of rotation of the plane of polarisation produced by an optically active substance depends on the concentration of the optically active material in a solution.

The use of decimetre as unit of length makes it easier to define specific rotation. You can as well use cm or meter as unit for length.

Let us now understand how the angle of rotation of the plane of polarisation varies with concentration. Consider a column of solution of length l cm (l /10 decimetre). Suppose that, at temperature t°C, the solution contains m g of optically active substance per cubic centimetre (c.c.) of the solution. Let us also assume that when a beam of linearly polarised light is passed through this column of solution, its plane of polarisation is rotated by an angle θ. The angle of rotation θ is given by

$$\theta = slm/10 \tag{2.6}$$

where s is called the **specific rotation** of the substance. It is defined as the rotation (in degree) produced by a column of solution of one decimetre length containing one gram of optically active substance per c.c. of the solution. Eq. (2.6) shows that the angle of rotation of the plane of polarisation depends on the amount of optically active substance present in the solution.

Now, suppose that c is the percentage strength (that is, concentration) of the solution. That is, c g of active substance is present is 100 c.c. of the solution. Then, we can write

$$m = c/100 \text{ g} \tag{2.7}$$

On substituting this value of m in Eq. (2.6), we get

$$\theta = slc/1000 \tag{2.8}$$

Eq. (2.8) shows how angle of rotation of the plane of polarisation is related to the concentration of a solution containing an optically active substance. You will use this relation in the present experiment to determine the concentration of a given solution. This relation can also be used to determine the value of the specific rotation of an optically active substance. To carry out these experiments, you will require a polarimeter. We, therefore, now familiarise you with a polarimeter and other necessary apparatus.

2.3 DESCRIPTION OF APPARATUS

The most important apparatus used in this experiment is a polarimeter. It is used for measuring the rotation of the plane of polarisation of light when it is made to pass through an optically active solution. As such, the operation of a plarimeter is very simple. Let us learn about it now.

2.3.1 Polarimeter

The simplest form of polarimeter consists of a polariser and an analyser. But, in a physics laboratory, we use a modified version of this simple arrangement. It is shown in Fig. 2.7a.

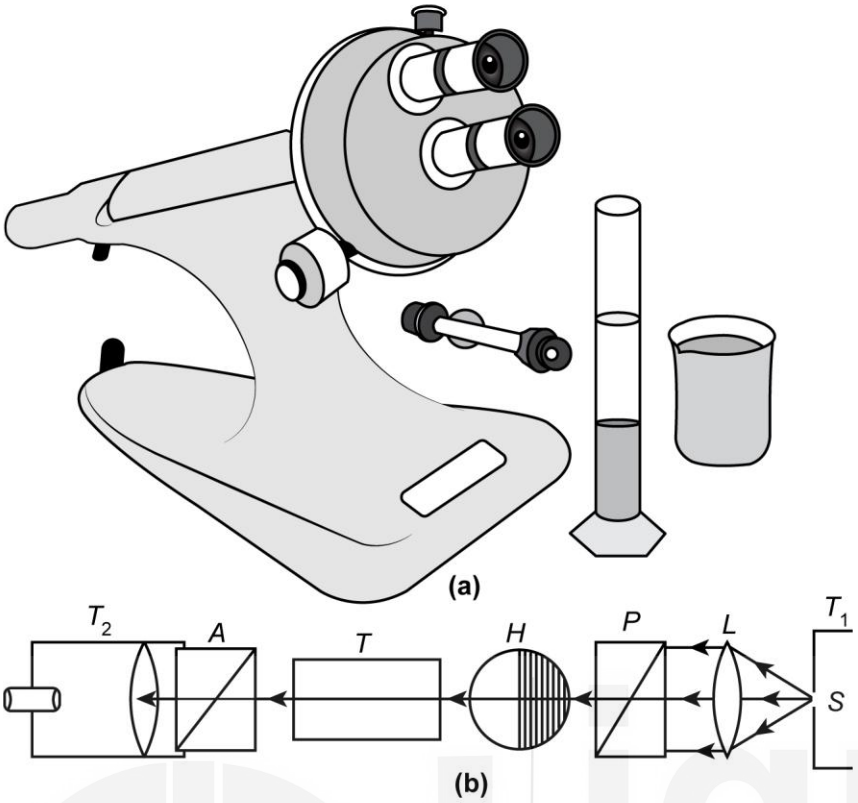


Fig. 2.7: **a) A polarimeter; b) Schematic diagram of a polarimeter.**

Refer to Fig. 2.7b which depicts the schematic diagram of a polarimeter. The tube T_1 containing a source of light holds a slit S whose width and position can be altered. This slit is placed in the focal plane of the collimating lens L. Therefore, the light from slit S can be considered to be in the form of plane waves. These waves reach a polariser P, in the form of a Nicol prism, which produces plane polarised light. This polarised light is then made to pass through a half-shade plate or a biquartz, H. (You will learn about the need and function of half-shade plate and biquartz shortly.) There is space in the main frame of the polarimeter to hold a tube T, which is filled with distilled water or a solution of an optically active material to be investigated. The two ends of the tube T are closed by optically plane glass plates with metal caps.

Another Nicol prism A, which acts as an analyser, is placed in another tube, T_2 in front of a low power telescope. As the tube T_2 is rotated, the vernier attached to the tube also rotates. This arrangement is used to determine the angle of rotation of the plane of polarisation. The axes of tubes T_1, T and T_2 are made to coincide with the same horizontal straight line.

In a simple polariser-analyser system, it is difficult to observe changes in the intensity of illumination for small rotations of the analyser from the position of extinction. To overcome this limitation and thereby achieve greater accuracy in measuring the rotation, optical components such as the half-shade plate or the biquartz are used in a polarimeter. We shall now briefly discuss these devices.

2.3.2 Half-Shade Plate

It is a circular plate (Fig. 2.8) whose one half, G is made of glass and the other half, Q is made of quartz. Here, YY' denotes the line of junction of the two halves. The thicknesses of both the halves are equal and the optic axis of quartz half is on its surface and parallel to YY'.

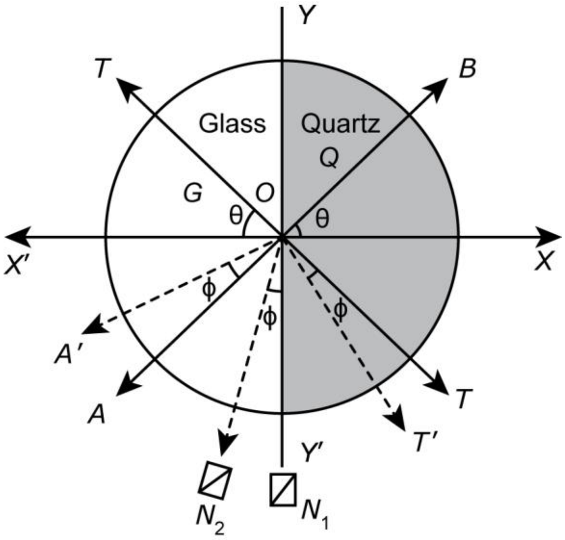


Fig. 2.8: **A half-shade plate used in a polarimeter.**

Recall from Unit 5 of BPHCT-137 that the optic axis refers to a direction in a birefringent crystal such that, if a ray of light passes along the optic axis, it does not suffer birefringence (that is, double refraction). The optic axis does not refer to a (fixed) line in a crystal; it refers to a direction. This implies that all rays passing through a crystal along a direction parallel to the optic axis of the crystal will pass through the crystal without suffering double refraction.

Now, to understand the function of the half-shade plate, consider that a linearly polarised light, in which vibrations of $\vec{\mathbf{E}}$ field are parallel to *AB,* is incident on the half-shade plate (Fig. 2.8). Suppose that the field vibrations make an angle θ with XX', a line perpendicular to the optic axis YY' of quartz. Then, vibrations of the $\vec{\mathbf{E}}$ field of the incident light falling on glass half (*G*) are not altered and hence they remain parallel to *OA* after emerging from the glass half. But, the vibrations of the $\vec{\mathbf{E}}$ field incident on the quartz half (along *OB*) split into two components because quartz exhibits birefringence. One component is parallel to the optic axis YY' (and corresponds to the *e*-ray), while the other is perpendicular to the optic axis (and corresponds to *o*-ray).**The thickness of the quartz half of the half-shade plate is chosen so that a phase difference of π (or path difference of $\lambda/2$) is produced between the emergent *e*- and *o*-rays.** Now, you may recall from Unit 5 of BPHCT-137 that a half-wave plate rotates the plane of polarisation of a linearly polarised light by 90 degrees. Hence, the vibrations corresponding to the emergent *e*- and *o*-rays from quartz half combine to form a linear polarised light whose electric field vibrations are along *TOT* inclined with OX' at an angle θ.

In a birefringent crystal, an incoming ray of light is split into two rays namely ordinary ray (*o*-ray) and extraordinary ray (*e*-ray). *o*-ray refers to the ray of light which obeys Snell's law of refraction and the *e*-ray refers to the one which does not obey Snell's law.

If a Nicol prism (analyser) is held at position N_1 with its principal section parallel to YY' and bisecting $\angle AOT$, the components of *OA* (from glass) and *OT* (from quartz) entering the Nicol are equal, i.e., intensity is same. Hence both halves of the half-shade plate will appear equally bright.

Two positions N_1 and N_2 of the Nicol correspond to two settings of the analyser fitted in tube T_2 in the polarimeter.

Now suppose both the $\vec{\mathbf{E}}$ field vibrations *OA* and *OT* are rotated in the same direction through the same angle ϕ to their new positions OA' and OT', respectively. In this situation, the amplitude of the component of OT' entering the Nicol at N_1 will be greater than that of OA'. The quartz half will, therefore, appear brighter than glass half. However, if the Nicol is brought to the position N_2 by rotating it through an angle ϕ, so that principal section of Nicol at N_2 again bisects the $\angle A'OT'$, the glass half and the quartz half will again appear equally bright. Note that, if this rotation of the plane of polarisation by an angle

ϕ is produced by an optically active substance, it can be measured in terms of the angle of rotation of the analyser fitted in tube T_2 in the polarimeter. Thus the angle of rotation of analyser equals the angle of rotation of the plane of polarisation.

In many polarimeters, instead of the half-shade plate, a biquartz is used to detect and accurately measure the rotation of the plane of polarisation. Consult your counsellor to know details of half-shade plate or biquartz used in your polarimeter. Whether or not you are using a biquartz, it is worthwhile to know how a biquartz works. Therefore, for inclusive coverage, we have discussed it in the following sub-section.

2.3.3 Biquartz

From unit 5 of BPHCT-137, you know that quartz is a uniaxial crystal and an optically active substance. Due to its uniaxial nature, a beam of light passing through a quartz crystal splits in two linearly polarised beams in which electric field vectors are perpendicular to each other. Do you know that in the special case when the uniaxial crystal (like quartz) is cut perpendicular to its optic axis, the state of polarisation of the beam of light passing through it does not change? Further, depending on its crystal structure, quartz can exhibit *d*-rotatory as well as *l*-rotatory behaviours. Moreover, the extent of rotation depends on the wavelength of light passing through a quartz crystal. These characteristics of quartz are used to design biquartz to accurately measure the rotation of the plane of polarisation in polarimetry experiments.

Biquartz used in polarimeter is in the shape of a circular disc and as the name suggests, it is made of two semi-circular discs of quartz, each of which is cut perpendicular to the optic axis. One of the semicircular discs is levorotatory while the other is dextrorotatory. The thickness of the disc (~3.75 mm) is such that, for the mean yellow light from a normal white light source, the plane of polarisation undergoes a rotation of $\pi/2$. This rotation is clockwise in one-half of the disc and anti-clockwise in the other half.

In a polarimeter, the biquartz is placed in such a manner that the principal section, *PP′* of the polariser (Fig. 2.9a) is parallel to the diameter separating its two halves. When white light is incident on the biquartz, it disperses the blue, yellow and red lights. When the principal section of the analyser, *AA′* is parallel to that of the polariser, the yellow light disappears. This happens because $\vec{\mathbf{E}}$ field vibrations corresponding to yellow light are rotated by $\pi/2$ in opposite directions in the two halves of the biquartz and the emergent yellow lights from the two halves are out of phase and disappear. It means that from each half of the biquartz, you should see some red and some voilet light as these are transmitted (Fig. 2.9b). The two halves of biquartz exhibit essentially the same reddish-violet shade. This is very sensitive to any change in the alignment of the principal axes of the polariser and analyser. For this reason, it is also known as the sensitive or transition tint or the **tint of passage** of the biquartz.

A small rotation of the analyser (~1°) causes one half of the field of view to become distinctly red and the other half to become violet (Fig. 2.9c). While performing the experiment, you have to rotate the analyser so that both halves of the field are of the same colour. Thus, you can set the analyser for a colour match very accurately. The tint of passage occurs for two settings of the vernier. As in the case of half-shade plate, the angle of rotation of the analyser (which leads to colour match of the two halves of the biquartz) gives the angle of rotation of the plane of polarisation.

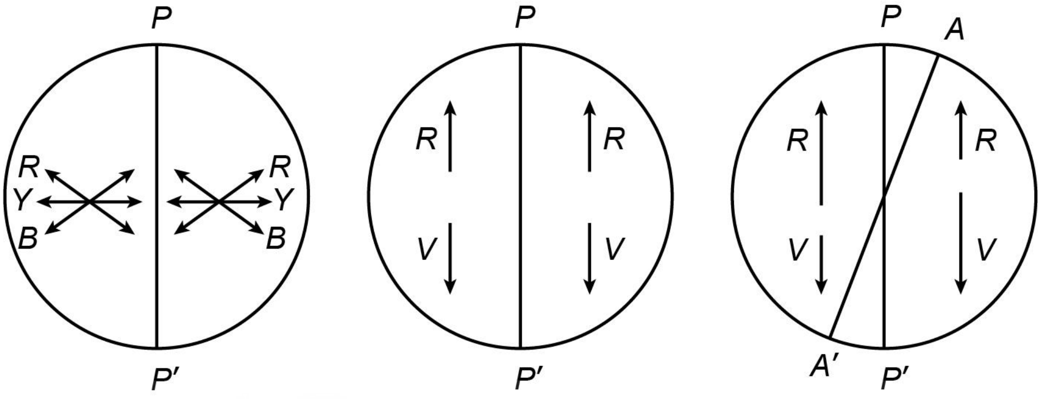


Fig. 2.9: **a) A biquartz; b) Intensities (depicted by the length of arrows) of the light of different colours emerging from a biquartz when the principal axes of the polariser and analyser are parallel; c) Intensities (depicted by the length of arrows) of the lights of different colours emerging from a biquartz when the analyser is rotated.**

With the above background knowledge about polarisation of light, working of polarimeter, and functions of half-shade plate and biquartz, you are equipped fully to perform the experiment. But before that, we would like you to answer a SAQ!

SAQ 1 **- Half-shade plate and biquartz**

Which arrangement – half-shade plate or biquartz – did you get in the polarimeter in your physics laboratory? Is it appropriate for the light source you will use for the experiment?

2.4 PROCEDURE

Before performing the actual experiment, you have to take care of some preliminaries. We first outline these.

Preparation of Stock Solution of Given Strength (or Concentration)

In this experiment, you will have to work with solutions of different concentrations to determine the relation between the angle of rotation of the plane of polarisation and concentration of substance in the solution. Therefore, you should first prepare solution of maximum concentration (say, 20%) by volume. To do so, follow the steps given below:

1. To prepare the stock solution of 20% concentration of sugar(the optically active substance), put 20 g of sugar in the clean and dry beaker/flask.

First add 50 ml of water and stir till sugar dissolves. Add more water to this solution to make the total volume 100 ml (c.c.). Filter the solution in a clean beaker. This is the sugar solution of 20% concentration. **This is your stock solution.**

2. Now, you only have to add appropriate amount of distilled water in a given volume of the stock solution of 20% concentration to obtain solutions of lower concentrations as described below.
3. Take 50 ml of above stock solution of 20% concentration in a beaker and add 50 ml water to it. Mix thoroughly. This makes sugar solution of 10% concentration.
4. Take 50 ml of sugar solution of 10% concentration and add 50 ml of water to it so that the volume of the solution becomes 100 ml. Mix thoroughly. This makes the sugar solution of 5% concentration.
5. Repeat the above step to get sugar solutions of 2.5% concentration and 1.25% concentration.
6. Keep these solutions of different concentrations properly labeled.

Now perform the following experiments.

2.4.1 Relation between the Angle of Rotation of the Plane of Polarisation of Light and the Concentration of Solution

1. Measure the length l of the tube T (Refer to Fig. 2.7b) between the two inner surfaces of the end plates with the help of a scale.
2. Determine the least count of the vernier attached to tube T_2.
3. Illuminate the slit S by sodium light (if your polarimeter is fitted with half-shade plate) or white light (if your polarimeter is fitted with biquartz). You should consult your academic counselor and know whether the polarimeter is fitted with half-shade plate or biquartz .
4. Fill the tube T completely with distilled water. You should remove all air bubbles from inside the tube. If some air bubble(s) persist in the tube, you will not obtain correct value of angle of rotation. Why? Discuss with your Counsellor.

SAQ 2 **- The polarimeter tube**

The cap of the tube is made of glass. Suppose that after filling the tube, you have screwed the cap rather tightly. Will it affect measurements? How and why?

---

5. Put the tube T in its proper position in the polarimeter.
6. Rotate the tube T_2 (which is fitted with analyser) until the two halves of the half shade plate are equally bright (or the two halves of the biquartz have the same colour). Enter the readings for the positions of the two verniers (V_1 and V_2) of tube T_2 in Observation Table 2.1.

7. Repeat step 6 three or four times and determine the mean values X_0 and Y_0 for the 1st vernier (V_1) and the 2nd vernier (V_2), respectively.

Once analyser is adjusted in correct position with respect to the polariser, you should not disturb/touch the polariser position during one complete set of observations. Why? This is because it may change the plane of polarisation of the incident light.

Observation Table 2.1: Vernier readings when the tube contains pure water

(i) Length of the tube T between internal faces of the end points =…..

(ii) Least count (LC) of vernier of tube T_2 =............

Sl. No.	**Reading for 1st vernier (V_1)**				**Reading for 2nd vernier (V_2)**			
	Circular scale S_1	**Vernier scale reading** $(V = (V_1 \times \text{LC}))$	**Total** $(S_1 + V)$	**Mean** (X_0)	**Circular scale** S_2	**Vernier scale reading** $(V = (V_2 \times \text{LC}))$	**Total** $(S_2 + V)$	**Mean** (Y_0)
1.								
2.								
3.								

Mean value of the 1st vernier, X_0 = ………..

Mean value of the 2nd vernier, Y_0 = …………

8. If your polarimeter is fitted with a biquartz, then the tint of passage will be observable at an angle say, θ_P. Then, record the observations on brightness / colour at $\theta_P - 2^\circ$, $\theta_P - 1^\circ$, $\theta_P + 1^\circ$, $\theta_P + 2^\circ$ in Observation Table 2.2. You have to prepare this table (Observation Table 2.2) yourself.

Observation Table 2.2: Vernier readings when the tube contains pure water

9. Remove water from tube T, wash it with solution of given concentration once or twice before you fill it completely with the solution.

10. Look through tube T_2. What do you observe? If the polarimeter contains half-shade plate, you are likely to observe that its two halves are unequally bright. If the polarimeter contains biquartz, its two halves are likely to be of different colours. This happens due to rotation of the plane of polarization of the linearly polarised light beam as it passes through the solution.
11. Rotate the tube T_2 until the two halves of the half-shade plate become equally bright or the two halves of the biquartz are of the same colour. Enter your vernier readings in Observation Table 2.3.
12. Repeat steps 9, 10 and 11 for solutions of other concentrations.

SAQ 3 - **Vernier readings**

Record the difference between the readings of V_1 and V_2 and comment on your observation.

Observation Table 2.3: Vernier readings when the tube *T* is filled with solutions of different known concentrations

Sl. No.	**Concentration of the solution (%)**	**Reading for 1st vernier (V_1)**			**Reading for 2nd vernier (V_2)**		
		Circular scale (*S*)	**Vernier scale** ($V = (V_1 \times \text{LC})$)	**$X = (S + V)$**	**Circular scale (S')**	**Vernier scale** ($V' = (V_2 \times \text{LC})$)	**$Y = (S' + V')$**
1.							
2.							
3.							
4.							

You can now obtain the angle of rotation from the two vernier readings as (take value of X_0 and Y_0 from Observation Table 2.1):

$$\theta_1 = X - X_0$$

$$\theta_2 = Y - Y_0$$

The mean angle of rotation is

$$\theta = \frac{\theta_1 + \theta_2}{2}$$

Record the mean angle of rotation as a function of concentration in Observation Table 2.4. You may note that this table is to be tabulated using Observation Table 2.1 and 2.3.

Observation Table 2.4: Angle of rotation as a function of concentration

Sl. No.	Concentration of the solution (%)	Angle of rotation for the first vernier $\theta_1 = X - X_0$ (deg)	Angle of rotation for the second vernier $\theta_2 = Y - Y_0$ (deg)	Mean angle of rotation $\theta = \frac{\theta_1 + \theta_2}{2}$ (deg)

Now plot a graph between concentration, *c* (taken along *x*-axis) and θ (taken along *y*-axis) as obtained from Observation Table 2.4. The graph should be a straight line passing through the origin. From the slope, (θ/*c*) of this graph you can calculate the specific rotation, *s* produced by the solution using Eq. (2.8).

Result: Specific rotation of the given solution = ……………………

2.4.2 Determination of the Concentration of a Solution

1. Rinse the tube *T* with stock solution of unknown concentration, *c* (say). The solute is of course the same as in Sec. 2.4.1 but its quantity in the solution is unknown.
2. Fill the tube *T* completely with the solution of unknown concentration and place it in proper position.
3. Repeat steps 9, 10 and 11 of Sec. 2.4.1 above and enter your vernier readings in Observation Table 2.5. Take X_0 and Y_0 from Observation Table 2.1. Determine the mean value of rotation (θ) as in the previous case (Sec. 2.4.1). You should take at least four readings and calculate mean values of *X* and *Y*.

Observation Table 2.5: Determination of the concentration of solution

Vernier position	Reading on vernier				Rotation for the vernier	Mean rotation $\theta = \frac{\theta_1 + \theta_2}{2}$	Percentage concentration of the solution, *c* (%)
	Circular scale (*S*)	Vernier scale (*V*)	Total (*S* + *V* × LC)	Mean			
1^{st}				*X* =	$\theta_1 = (X - X_0)$ =		
2^{nd}				*Y* =	$\theta_2 = (Y - Y_0)$ =		

For calculating *c* in the above table, use the value of *s* as obtained by the graph plotted for measurements in Sec. 2.4.1 and use Eq. (2.8).

Result: Concentration of the unknown solution = ………%.

Write this result in Observation Table 2.5. You may now like to analyse the results.

EXPERIMENT 3

CAUCHY'S CONSTANTS OF THE MATERIAL OF A PRISM

Structure

3.1 INTRODUCTION

Reflection and refraction are the basic properties of light that you have studied in detail in your school physics classes. A brief introduction to the phenomenon of refraction has been provided in Experiment 1 of this course where you learnt how to obtain the refractive index of the material of a prism using sodium light.

It is interesting to explore what happens to refractive index when composite light such as from a mercury lamp source is made to fall on a prism.

In this experiment, you will use the skills developed in Experiment 1 to set the spectrometer, determine the angle of the prism and the angle of minimum deviation for each wavelength of mercury light. Using these observations, you can determine the refractive index for each wavelength. This data will then be utilized to determine the Cauchy's constants for the material of the prism.

Expected Skills

After performing this experiment, you should be able to:

- set-up the spectrometer and calculate its least count;

- determine the angle of the prism and angle of minimum deviation for light of given wavelength (colour);
- plot a graph between refractive index corresponding to a wavelength as a function of $1/\lambda^2$; and
- calculate Cauchy's constants for the material of the prism.

Before proceeding further, we list the apparatus that you will use to perform this experiment.

Apparatus Required

Mercury (Hg) lamp, prism, spectrometer (collimator, prism table, telescope), magnifying glass, spirit level, torch/lamp, scale, cleansing cloth.

3.2 THEORETICAL BACKGROUND

From Sec. 1.2.2, Experiment 1 of this course, you will recall that the refractive index of a prism for light of a given wavelength is given by Eq. 1.11:

$$\mu = \frac{\sin\frac{A+\delta_m}{2}}{\sin(A/2)} \tag{3.1}$$

where *A* is the angle of the prism and δ_m is the angle of minimum deviation for the given wavelength (colour).

You may also recall from Experiment 1 that, for a given wavelength, the angle of deviation is minimum when the angle of incidence is such that ray inside the prism becomes parallel to the base of the prism. For this angle of deviation, the object and the image are at the same distance from the prism, and the image is the brightest. Refer to Sec. 1.4 to quickly revise the steps used to set up the experiment to determine the angle of the prism and the angle of minimum deviation using the sodium light. In this experiment, you can use a particular colour or white light to determine the angle of prism.

Cauchy's equation is an empirical relation between the refractive index of a material and the wavelength of light:

$$\mu_\lambda = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \ldots\ldots \tag{3.2}$$

where constants *A*, *B*, *C* are referred to as Cauchy's constants. As you can see, this relation predicts that as wavelength of light increases, the refractive index decreases. Typically, it is sufficient to use only the first two terms of this equation:

$$\mu_\lambda = A + \frac{B}{\lambda^2} \tag{3.3}$$

In this experiment, you will determine Cauchy's constants *A* and *B* using the form of Cauchy's equation expressed in Eq. (3.3). Cauchy's constants will be determined by plotting a graph of μ_λ versus $\frac{1}{\lambda^2}$ once refractive index corresponding to different wavelengths (colors) has been determined.

In Experiment 1, you worked with sodium vapor lamp which emits a doublet with wavelengths ~ 589.0 nm and 589.6 nm. It means that with sodium vapor lamp, you can determine the refractive indices of the prism for two wavelengths only. (However, in view of very small difference between the wavelengths of the sodium doublet, we considered the light emitted by the sodium source as of single wavelength carried out calculations accordingly in Experiment 1.) But the spectrum of a mercury vapour lamp consists of several (seven) wavelengths and can be used to study the variation of refractive index with wavelength. The spectra of a sodium vapor lamp and mercury vapor lamp are shown in Fig. 3.1.

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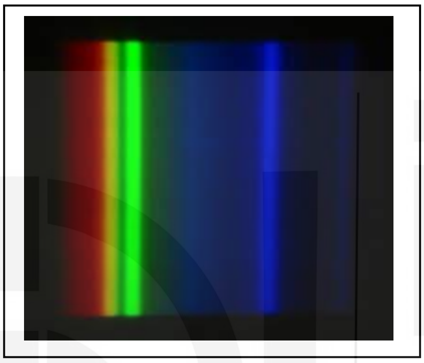


Fig. 3.1: **A representative emission spectrum of a mercury-vapour lamp [**Picture credit: *D-Kuru, CC BY-SA 2.0 AT <https://creativecommons.org/licenses/by-sa/2.0/at/deed.en>, via Wikimedia Commons***]**

You may now like to know as to what happens when a composite light like that from a mercury lamp enters a prism. You may recall from your earlier classes that an interesting phenomenon of dispersion is observed in which light splits into its constituent colours (of different wavelengths) as shown in Fig. 3.2.

This is because the refractive index of the material of the prism is different for different wavelengths. The refractive index increases from red to violet, so the angle of deviation is greater for violet than for red, as you can note from Eq. 3.2.

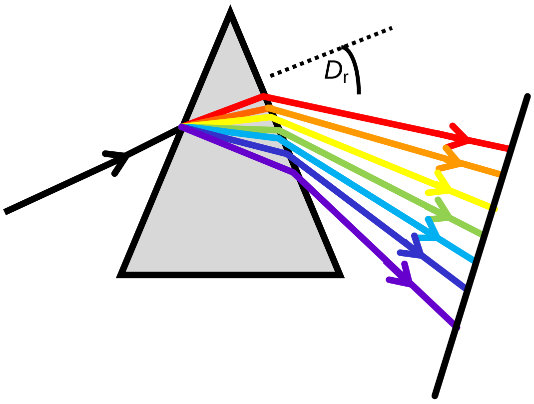


Fig. 3.2: **Dispersion of light from a prism. The angle of deviation is δ_r for the red colour.**

3.3 MEASUREMENT OF THE ANGLE OF PRISM AND ANGLE OF MINIMUM DEVIATION

First, you must follow the steps outlined in Sec. 1.4.1, Experiment 1 to set up the spectrometer and focus the collimator for parallel light. Then, follow the instructions given here for taking the measurements required to calculate Cauchy's constants of the prism.

3.3.1 Angle of Prism using Sodium Light

To determine the angle of prism, follow the steps outlined in Sec. 1.4.2 using one particular wavelength emitted by mercury vapour lamp. Record your readings in Observation Table 3.1. Take at least two sets of readings.

Least Count (LC) of vernier of the spectrometer = ...

Wavelength of light used (sodium light) = ...

Observation Table 3.1: Angle of Prism (*A*)

No. of Observation	**Vernier**	**1st Position of Telescope**			**2nd Position of Telescope**			**Difference = 2*A***	**Angle of Prism *A***
		MSR	**VSR**	**Total**	**MSR**	**VSR**	**Total**		
1	I V_1								A_1=
	II V_2								A_2=
2	I V_1								A_3=
	II V_2								A_4=

Angle of the Prism $A = \frac{A_1 + A_2 + A_3 + A_4}{4} =$ ....°

3.3.2 Angle of Minimum Deviation for Different Colours using Mercury Light

After determining the angle of the prism, you have to determine the angle of minimum deviation for each of the prominent colours of mercury light, namely violet, indigo, blue, green, yellow, orange and red following the steps outlined in Sec. 1.4.2, Experiment 1. Record your readings in Observation Table 3.2. Take at least two sets of readings for each colour. Calculate the mean value of the angle of minimum deviation for each colour.

Observation Table 3.2: Angle of minimum deviation δ_m for light of different colours

Sl. No	Color of Light	No. of Observations	Vernier	Minimum Deviation Ray			Direct Ray			Difference $= \delta_m$	**Mean* Angle of Minimum Deviation**
				MSR	VSR	Total	MSR	VSR	Total		
1.	Violet	1	I V_1							δ_{m1} =	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
2.	Indigo	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
3.	Blue	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
4.	Green	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
5.	Yellow	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
6.	Orange	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	
7.	Red	1	I V_1							δ_{m1}=	
			II V_2							δ_{m2} =	
		2	I V_1							δ_{m3} =	
			II V_2							δ_{m4} =	

* Mean Angle of Minimum Deviation

$$\delta_m = \frac{\delta_{m1} + \delta_{m2} + \delta_{m3} + \delta_{m4}}{4} = \ldots\ldots\ldots\ldots^\circ$$

We now calculate the refractive index for each color of light and the Cauchy's Constants *A* and *B*.

3.4 CALCULATIONS

3.4.1 Refractive Index for Different Colours of Light

You can calculate the refractive index μ_λ for each colour (with a typical wavelength as given in the margin remark) using Eq. (3.1). Enter the results of your calculations in Observation Table 3.3.

The standard values of wavelength (λ) for the different colours are:
Violet: 400 nm

Indigo	: 420 nm
Blue	: 450 nm
Green	: 550 nm
Yellow	: 580 nm
Orange	: 600 nm
Red	: 650 nm

(Source: brittanica.com/science/color/The-visible-spectrum)

Table 3.3: Refractive indices for different colours

Sl. No.	**Colour of Light**	**Wavelength λ**	**Angle of Minimum Deviation**	**Refractive Index μ_λ**
1.				
2.				
3.				
4.				
5.				
6.				
7.				

3.4.2 Calculation of Cauchy's Constants

We now calculate the Cauchy's Constants using Eq. (3.3).

To do this, you have to plot a graph of the inverse of the square of the wavelength $\left(\frac{1}{\lambda^2}\right)$ for each wavelength λ along the *x*-axis and the corresponding refractive index, μ_λ for that wavelength along the *y*-axis. Do the needed calculations and enter the data required for plotting this graph in Observation Table 3.4. The values of μ_λ and λ are to be taken from Observation Table 3.3.

Observation Table 3.4: Values of μ_λ and $\frac{1}{\lambda^2}$

Sl. No.	**Wavelength** λ	$\frac{1}{\lambda^2}$	**Refractive Index** μ_λ
1.			
2.			
3.			
4.			
5.			
6.			
7.			

You should get a graph as the one shown in Fig. 3.3. While plotting the graph, the scales should be so chosen that full span of the graph is utilised. By doing so, you will minimise error in your calculations.

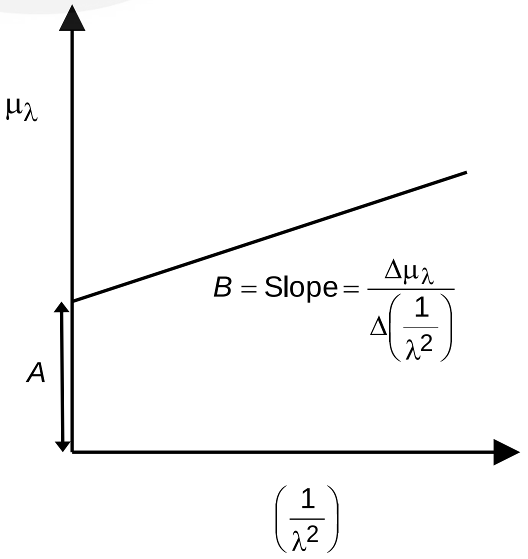


Fig 3.3: **Plot of μ_λ with $\frac{1}{\lambda^2}$**

The values of A and B are calculated as the intercept on the y-axis and the slope of the graph, respectively. To calculate the slope, you should use the maximum possible intercept of the straight line.

Result:

The values of the Cauchy's constants A and B for the material of the prism are:

A = ...

B = ...

EXPERIMENT 4

WAVELENGTH OF SODIUM LIGHT USING FRESNEL'S BIPRISM

Structure

4.1 INTRODUCTION

As a child, you may have enjoyed blowing soap bubbles and seeing bright rainbow colours reflected from them. On a rainy day, you must have also observed brilliant, though irregular, colour patterns on the wet road surface due to a thin layer of oil spilt by a motor vehicle. You may have also realised that colour patterns change if you look at them from different angles. Have you ever looked at a fairly transparent piece of silk or polyester cloth from a distance? If you do so, you would observe patterns of bright and dark bands. The bright and dark bands so produced are known as **interference fringes**. All the phenomena described above arise due to interference of light waves. You have learnt about interference of light in Unit 6 of the fourth semester course entitled Waves and Optics (BPHCT-137).

The simplest demonstration of interference of light waves was devised by Thomas Young. You have learnt about Young's double slit experiment in Unit 6 of BPHCT-137. You may recall that in this experimental setup, monochromatic light from a point source is made to give rise to two coherent sources by placing two closely spaced narrow slits in its path. The superposition of waves from these two coherent sources produces a clear interference pattern comprising bright and dark fringes on a screen placed some distance away. Do you know why we need coherent sources to observe interference pattern?

Two sources are said to be **coherent** if light waves originating from them are of the same frequency and have a constant phase difference between them.

The coherent sources can be produced by a variety of experimental set-ups. In the theory course BPHCT-137, you have learnt that unlike Young, Fresnel used a biprism to produce two coherent sources. In this experiment, you will learn to obtain interference pattern using a biprism and determine fringe width. (It is the distance between two consecutive dark (or bright) fringes.) This will enable you to determine the wavelength of the incident monochromatic light.

Expected Skills

After performing this experiment, you should be able to:

- set up an optical bench to observe interference pattern;
- use a biprism to obtain interference fringes;
- determine the distance between two virtual coherent sources;
- determine the factors on which fringe width depends; and
- determine the wavelength of sodium light.

You will require the following apparatus for this experiment.

Apparatus Required

A biprism, optical bench with uprights, sodium vapour lamp, slit, micrometer eye-piece and a convex lens of short focal length.

4.2 INTERFERENCE OF LIGHT

Interference is a phenomenon in which waves, under certain circumstances, reinforce (intensify or weaken) each other. The phenomenon is understood on the basis of the principle of superposition of waves. You have learnt this principle in your school physics course as well as in Unit 2 of the course BPHCT-137. You know that two identical progressive mechanical waves travelling along a wire, fixed at the ends, in opposite directions give rise to stationary waves. The stationary waves are characterised by succession of nodes and anti-nodes. The nodes are positions of minimum intensity whereas anti-nodes are positions of maximum intensity. In other words, there is a redistribution of energy carried by the two superposing waves. This redistribution of energy is one of the most significant characteristics of the interference phenomenon.

In Unit 6 of the BPHCT-137 course, you learnt that the interference phenomenon is also observed with light when light from two coherent sources superpose. When two or more light waves of same frequency and having constant phase relation between them are superposed, the intensity of the resultant light in the region of superposition is found to vary from point to point. At some points, the intensity equals the sum of the intensities of individual waves while at some other points it is almost zero. (These are known as points of maxima and minima, respectively.) This is termed as the phenomenon of **interference**. The interference pattern comprises a series of regularly spaced maxima and minima. If the resultant intensity is zero, or in general, less than what we expect from individual waves, we have **destructive interference** (seen as dark fringes/bands). On the other hand, if resultant intensity is greater than the intensities of individual waves, we have **constructive interference** (seen as bright fringes/bands in the pattern).

In the present experiment, you will obtain interference pattern produced by light form two coherent sources and make certain measurements to determine the wavelength of the light used. For this purpose, you need to have an expression which relates the experimentally measured quantities (fringe width, in the instant case) with the wavelength of light used. Let us now obtain the expression relating fringe width and wavelength of light used to obtain the interference pattern. (You have derived this expression in Unit 6 of BPHCT-137. But, we are giving it here for the sake of completeness.)

Suppose that a narrow slit *S* is illuminated by a monochromatic source of light. This, in turn illuminates two other narrow equidistant slits S_1 and S_2 (called double slit) separated through a distance *d* from each other, as shown in Fig. 4.1. The interference pattern is obtained on a screen placed at a distance, say *D,* from the double-slit and parallel to the plane containing these slits.

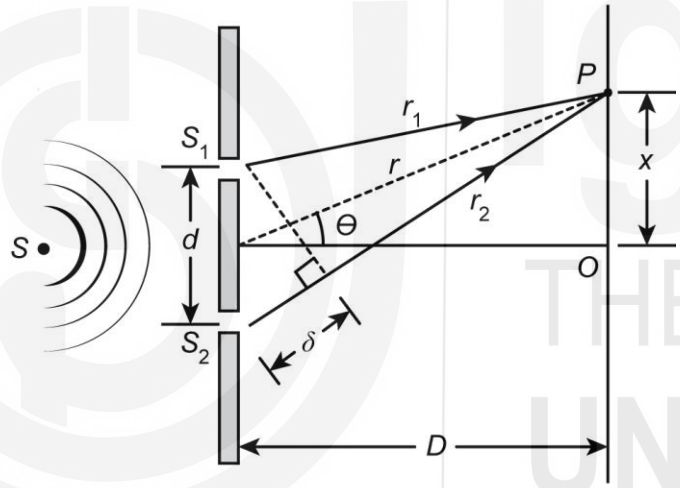


Fig. 4.1: **Schematic diagram of the double slit arrangement used to observe interference of light.**

Let us consider a point *P* on the screen which is the nearest maxima or minima from the origin. Suppose that the two waves emanating from slits S_1 and S_2 respectively are given as

$$y_1 = a\sin(\omega t - kx) \tag{4.1a}$$

$$y_2 = a\sin(\omega t - kx + \phi) \tag{4.1b}$$

Note that we have chosen the amplitude of both the waves equal to *a* because the two slits are very close to each other. Further, the phase difference ϕ arises because the wave originating from slit S_2 travels an extra distance as compared to the wave originating at slit S_1. Now, let us know as to what happens when these waves reach point *P* on the screen. For simplicity, let us take point *P* to be the origin so that the *kx* term in Eqs. (4.1a) and (4.1b) can be dropped. Thus, at point *P*, we can write the displacements due to the two waves as

Note that we are discussing here the interference of light caused due to superposition of two light waves (electromagnetic waves). Thus, you should keep in mind that the displacements y_1 and y_2 used in Eqs. (4.1a) and (4.1b) actually represent the magnitude of the electric fields associated with the light waves emanating from slits S_1 and S_2 respectively.

$$y_1 = a\sin\omega t$$

$$y_2 = a\sin(\omega t + \phi)$$

Note that the slits S_1 and S_2 are essentially coherent sources. Therefore, the phase difference ϕ between the two waves is constant. Since a path difference of one wavelength corresponds to a phase difference of 2π radians, we can write

$$\phi = \frac{2\pi}{\lambda} \times (\text{path difference}) \qquad (4.2)$$

Refer to Fig. 4.1. We can write the path difference between S_1P and S_2P as

$$S_2P - S_1P = d\sin\theta \qquad (4.3)$$

where d is the separation between the slits S_1 and S_2. Thus we can write

$$\phi = \frac{2\pi}{\lambda} d\sin\theta \qquad (4.4)$$

$y = y_1 + y_2$

$= a\sin\omega t + a\sin(\omega t + \phi)$

Using the identity

$\sin A + \sin B =$

$2\sin(\frac{A+B}{2})\cos(\frac{A-B}{2})$

we can write

$y = a[2\sin(\omega t + \frac{\phi}{2})\cos(-\frac{\phi}{2})]$

$= 2a\cos(\frac{\phi}{2})\sin(\omega t + \frac{\phi}{2})$

Now, according to the superposition principle, the resultant displacement, y at P is given by (see the margin remark)

$$y = y_1 + y_2 = 2a\cos\left(\frac{\phi}{2}\right).\sin(\omega t + \frac{\phi}{2}) \qquad (4.5)$$

Eq. (4.5) shows that the expression for displacement y of the resultant wave at point P corresponds to a harmonic wave with amplitude $2a\cos\left(\frac{\phi}{2}\right)$. Further, you know that intensity of wave is proportional to the square of the amplitude. Thus, we can write the intensity of light at point P as

$$I = 4a^2\cos^2\left(\frac{\phi}{2}\right) \qquad (4.6)$$

Eq. (4.6) shows that the intensity is maximum ($= 4a^2$ or four times the intensity of either wave) if

$$\frac{\phi}{2} = n\pi \qquad n = 0, 1, 2, \ldots \qquad (4.7a)$$

and minimum (in fact, zero) if

$$\frac{\phi}{2} = \left(n + \frac{1}{2}\right)\pi \qquad n = 0, 1, 2, \ldots \qquad (4.7b)$$

Thus, by substituting the value of (ϕ/2) from Eq. (4.7a) in Eq. (4.4), we can write the **condition for constructive interference** as

$$\sin\theta_n = \frac{n\lambda}{d} \qquad n = 0, 1, 2, 3, \ldots \qquad (4.8a)$$

and from Eq. (4.7b) for **destructive interference** as

$$\sin\theta_n = \left(n + \frac{1}{2}\right)\frac{\lambda}{d} \qquad n = 0, 1, 2, 3, \ldots \qquad (4.8b)$$

Now, to obtain an expression for the fringe width, refer to Fig. 4.1 again. Let *OP* = *x.* Then, we can write

$$x = D\tan\theta \tag{4.9a}$$

Thus, the positions of the maxima and minima are given by

$$x_n = D\tan\theta_n \tag{4.9b}$$

where θ_n is given by Eqs. (4.8a) and (4.8b) for bright (constructive interference) and dark (destructive interference) fringes, respectively.

Finally, if the slit separation is much greater than the wavelength of light used $(d >> \lambda)$, then for non-zero values of *n*, the value of $\frac{n\lambda}{d}$ will be very small. Therefore, it readily follows from Eq. (4.8a) that θ_n will be very small. Then in the small angle approximation, we can take

The wavelength,
λ ~ 6000 Å ~ 0.6 μm.
And, the typical value of slit separation,
d ~ 1 mm.
So, $d >> \lambda$.

$$\sin\theta_n \approx \tan\theta_n \approx \theta_n$$

Hence, Eq. (4.9b) can be written as

$$x_n = D\,\theta_n \tag{4.10}$$

So, Eq. (4.8a), in small angle approximation, reduces to

$$\theta_n = \frac{n\lambda}{d} \tag{4.11}$$

Thus, from Eqs. (4.10) and (4.11), we get the position of the n^{th} bright fringe on the screen as

$$x_n = \frac{n\lambda D}{d} \qquad n = 0, 1, 2, 3, \ldots \tag{4.12}$$

Similarly, Eq. (4.8b), in small angle approximation, takes the form

$$\theta_n = \left(n + \frac{1}{2}\right)\frac{\lambda}{d} \tag{4.13a}$$

Thus, from Eqs. (4.10) and (4.13), we get the position of the n^{th} dark fringe on the screen as

$$x_n = \frac{\left(n + \frac{1}{2}\right)\lambda D}{d} \qquad n = 0, 1, 2, 3, \ldots \tag{4.13b}$$

You can create double slits by cutting very fine slits in a black art paper using a shaving blade. Then using an ordinary lamp, you should be able to obtain interference pattern. Discuss your findings with your peers as well as your academic counsellor.

Note that by using Eqs. (4.12) and (4.13.b), you can calculate the **fringe width** (that is, distance between two consecutive bright fringes or the distance between two consecutive dark fringes):

$$\beta = x_{n+1} - x_n = \frac{(n+1)\lambda D}{d} - \frac{n\lambda D}{d} = \frac{\lambda D}{d} \tag{4.14}$$

So, once we know the wavelength λ of the light, slit separation, *d* and the distance, *D* between the double slit and the screen, we can easily calculate the fringe width. However, in the present experiment, you will measure fringe width, *d* and *D* to determine the wavelength of light using Eq. (4.14).

In the above discussion on the phenomenon of interference of light, we confined to the double slit arrangement in which two coherent sources were obtained from a given source of light. But, the double slit arrangement (Fig. 4.1) has some inherent limitations which impact the quality of the interference pattern. If slits S_1 and S_2 are very narrow, the amount of light available for forming the fringes will be very small and the (bright) fringes will be of feeble intensity. Also, you can argue that these slits may diffract light and the observed pattern will not be interference pattern. To overcome such limitations, Fresnel designed an experimental set up to obtain interference pattern wherein the double slit arrangement was replaced by a biprism to create **virtual** coherent sources of light. He demonstrated that the light from such virtual sources gives rise to interference pattern. We will now briefly discuss Fresnel biprism arrangement.

4.3 FRESNEL'S BIPRISM AND COHERENT SOURCES

A biprism is made up of two identical prisms of very small (~ 0.5^0) refracting angles placed base to base. To understand how a biprism can be used for creating two coherent sources of light, refer to Fig. 4.2. S is a narrow vertical slit illuminated by monochromatic source of light. The light from S is made to fall symmetrically on the biprism having its refracting edges parallel to the slit. The light incident on each half of the prism is refracted by the corresponding refracting edge. This gives rise to virtual images S_1 and S_2 of the slit S located on its either side. The distance between S_1 and S_2 is *d*.

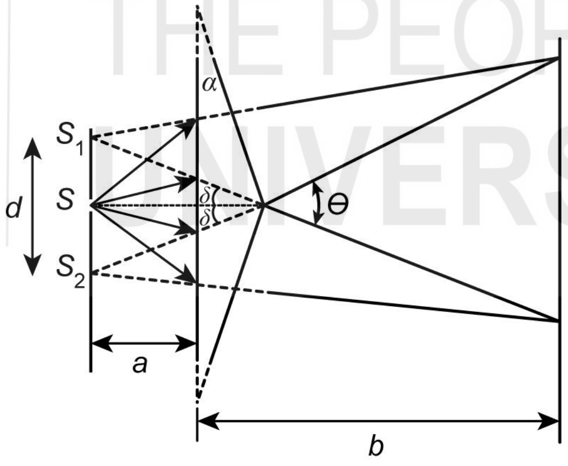


Fig. 4.2: **Formation of virtual images S_1 and S_2 of slit S by a biprism.**

These two virtual images S_1 and S_2 act as two coherent sources. S_1 and S_2 are fairly close to the source S. (S_1, S and S_2 are in the same plane) as the angles of deviation are small. You can verify from Fig. 4.2 that $SS_1 = SS_2 = a\delta$, where *a* is the distance between the source S and the biprism and δ is the angle of deviation. We know that angular deviation produced by a biprism is given by (see the margin remark)

$$\delta = (\mu - 1)\,\alpha$$

where μ is the refractive index of the material of the prism and α is base angle. Thus, we can write

You may recall from Experiment 1 that the prism equation is given as (Eq. (1.11)):

$$\mu = \frac{\sin\frac{A+\delta_m}{2}}{\sin(A/2)}$$

Since the biprism is very thin, the angle, *A* (which, in case of biprism, we have denoted by α) of the prism is very small and we can write

$$\sin\frac{\alpha+\delta}{2} = \frac{\alpha+\delta}{2}$$

$$\sin(\alpha/2) = \alpha/2$$

Thus, we can write

$$\mu = \frac{(\alpha+\delta)/2}{\alpha/2}$$

$$\mu\alpha = (\alpha+\delta)$$

$$\delta = (\mu - 1)\alpha$$

$$S_1S_2 = S_1S + SS_2 = d = 2a(\mu - 1)\alpha \tag{4.15}$$

If the eye-piece is held at a distance *b* from the biprism anywhere in the region of overlap of the two refracted beams, the distance of the pair of sources from the plane of interference will be

$$D = (a + b) \tag{4.16}$$

On substituting for *d* and *D* from Eqs. (4.15) and (4.16), respectively in Eq. (4.14), we get the expression for the fringe width as

$$\beta = \frac{(a+b)\lambda}{2a(\mu - 1)\alpha} \tag{4.17}$$

This result shows that we can calculate the wavelength of light once we have measured *a*, *b*, α and β, for a biprism of given refractive index.

Since biprism is very thin, the angle α is very small $(\approx 6 \times 10^{-3}\,\text{rad})$ and it is not convenient to measure it. So, Eq. (4.15) is not very useful for determining *d* in this experiment. We, therefore, resort to an alternative method called method of displacement, wherein *d* is connected to the separation between the images of the two virtual sources rather than α. You may like to know how this is achieved. The answer to this question is given in the following paragraphs.

A convex lens of short focal length (*f* ~ 15 cm to 20 cm) is introduced between the biprism and the eye-piece (Fig. 4.3). The eye-piece is kept at a large distance from the slit (5*f* > *D* > 4*f*). This condition on *D* minimises the error in the measurement of *d* (see the margin remark on the next page). The convex lens converges the two refracted beams. We can adjust its position to obtain clear well-defined images in the plane of the cross wires in the eye-piece. In fact, while performing the experiment, you will observe that once positions of slit, biprism and the eye-piece are fixed, there are two positions of the lens, shown as L_1 and L_2 in Fig. 4.3, for which clear images of S_1 and S_2 are obtained in the eye-piece. When the lens is at one of these positions (say at L_1), we obtain magnified images while in the other position (say L_2), we obtain diminished images of the sources.

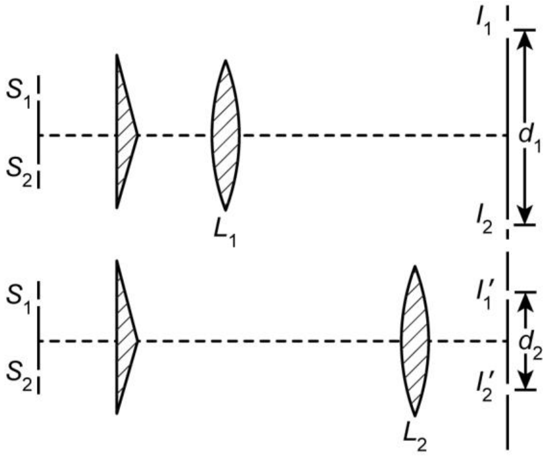


Fig. 4.3: **Displacement method to determine the distance between the coherent virtual sources in Fresnel biprism experiment. Two positions of the lens between the biprism and the eye-piece correspond to enlarged images I_1, I_2 and diminished images I_1', I_2' of S_1 and S_2.**

Suppose that the separation between the two magnified images as seen in the eye-piece is d_1. If the actual distance between the virtual sources S_1 and S_2 is d, the expression for magnification by the lens is given by

$$m_1 = \frac{d_1}{d} \tag{4.18a}$$

And, if d_2 is the distance between diminished images of S_1 and S_2, as seen in the eye-piece, the magnification is given by

$$m_2 = \frac{d_2}{d} \tag{4.18b}$$

Now, if u and v are distances of the object and the image, respectively, we can write from Fig. 4.3 that

$$u + v = D$$

or, $\quad u = D - v$

From the lens formula, we know that

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

On substituting for u, we can write

$$\frac{1}{v} + \frac{1}{D-v} = \frac{1}{f}$$

or

$$\frac{D-v+v}{v(D-v)} = \frac{1}{f} \Rightarrow \frac{D}{v(D-v)} = \frac{1}{f}$$

This can be rewritten as

$$v^2 - Dv + fD = 0$$

For real roots of the this quadratic equation, we must have

$$D^2 - 4fD > 0$$

or $\quad D > 4f \quad$ (4.19a)

Further, if the real roots are v_1 and v_2, then the sum of the roots is

$$v_1 + v_2 = D \tag{4.19b}$$

But, from Fig. 4.3, we have

$$u_1 + v_1 = u_2 + v_2 = D \tag{4.20}$$

where u_1, v_1 are the object and image distances when lens is in position L_1 and u_2, v_2 are object and image distances when the lens is in the position L_2. On substituting for $v_1 = D - v_2$ from Eq. (4.19b) in Eq. (4.20), we can write

$$u_1 + D - v_2 = D \quad \Rightarrow u_1 = v_2$$

On eliminating v_2 by combining Eqs. (4.19b) and (4.20), you can prove that $u_2 = v_1$. Since

$$m_1 = \frac{v_1}{u_1} \quad \Rightarrow \quad m_1 = \frac{v_1}{v_2}$$

The condition $D > 4f$ is a theoretical consideration (see Eq. (4.19a)) but the condition $5f > D$ arises from the practical consideration of minimising the error in the measurement of d, which is geometrical mean of d_1 and d_2. The error consideration for the condition can be obtained as follows:

$$d = \sqrt{d_1 d_2}$$

Taking logarithm of both sides, we get

$$\ln d = \frac{1}{2}\ln d_1 + \frac{1}{2}\ln d_2$$

On differentiation, we get

$$\frac{\Delta d}{d} = \frac{\Delta d_1}{2d_1} + \frac{\Delta d_2}{2d_2}$$

so that if we denote $\Delta d/d$ by e, then we can write

$$e = \frac{1}{2}(e_1 + e_2)$$

and

$$e_1 e_2 = \frac{\Delta d_1}{d_1} \cdot \frac{\Delta d_2}{d_2}$$

$$= \frac{\Delta d_1 \Delta d_2}{d^2}$$

$$= \text{constant}$$

Since $(e_1 + e_2)^2 = (e_1 - e_2)^2 + 4e_1 e_2$, $e_1 + e_2$ will be minimum when $e_1 = e_2$. This condition implies that

$$\frac{\Delta d_1}{d_1} = \frac{\Delta d_2}{d_2}$$

But $\quad \Delta d_1 = \Delta d_2$

$$\therefore \quad d_1 = d_2$$

That is, d_1 and d_2 should be almost equal.

Similarly, you can show that

$$m_2 = \frac{v_2}{u_2} = \frac{v_2}{v_1}$$

Hence, $m_1 \times m_2 = 1$

or $$m_1 = \frac{1}{m_2} \qquad (4.21)$$

The sum of the roots of a quadratic equation

$$ax^2 + bx + c = 0$$

is equal to $-b/a$. Here $b = D$ and $a = 1$. Therefore, sum of roots

$$v_1 + v_2 = D$$

On combining Eqs. (4.18a) (4.18b) and (4.21), we can write

$$d = \sqrt{d_1 d_2} \qquad (4.22)$$

That is, *d* is geometric mean of d_1 and d_2.

By combining Eqs. (4.16a) and (4.22), we can write the expression for the fringe width as

$$\beta = \frac{D\lambda}{d} = \frac{(a+b)\lambda}{\sqrt{d_1 d_2}} \qquad (4.23)$$

This expression for fringe width constitutes the working formula for this experiment. Note that all quantities appearing on the right hand side (*a*, *b*, d, d_1, d_2 and β) can be measured to determine the wavelength, λ of the light used in the experiment.

In the next Section, we outline the procedure for determination of wavelength of light using this working formula.

4.4 DETERMINATIOIN OF WAVELENGTH OF SODIUM LIGHT

In this experiment, you have to first obtain coherent sources using a biprism and then get interference fringes in the plane of the cross wires to measure the fringe width and determine the distance between the coherent sources. We now give the steps that you have to follow to adjust the apparatus to obtain interference fringes.

4.4.1 Adjusting the Apparatus

1. Refer to Fig. 4.4. It shows a sodium lamp, an optical bench with four uprights and an eye-piece.

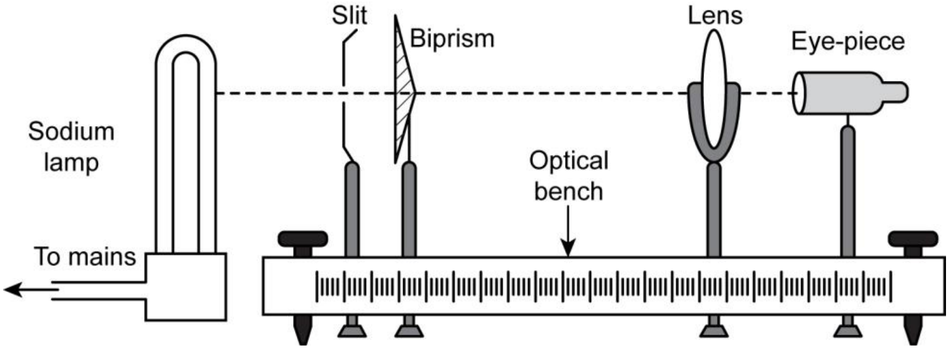


Fig. 4.4: **The experimental setup for observing interference pattern due to Fresnel's biprism.**

2. Arrange the sodium lamp at one end of the optical bench. The sodium lamp is normally kept in a rectangular box having a small rectangular opening on one side to allow light to pass.
3. Mount a slit of adjustable width on the first upright and the biprism on the second upright. You must note that the slit is provided with a screw to rotate it in its own plane. Using this screw, ensure that the slit is vertical. Keep the width of the slit very small.
4. Just like the slit, the biprism can also be rotated in its own plane. Also make sure that the edge of the biprism is parallel to the slit.
5. Now view the slit (illuminated by sodium light) through the biprism. Move your eye sideways. What do you observe? Does one of the bright vertical lines appear and disappear suddenly? **If it is so, then you can be sure that the edge of the biprism is exactly parallel to the slit.** If the bright line appears or disappears gradually from top to bottom, then the edge of the biprism is not parallel to the slit. Rotate the biprism in its own plane till it is exactly parallel to the slit. In doing so, remember to keep the slit and the biprism as close as possible 9about 15 cm apart).
6. Now, put the micrometer eye-piece at about 15 to 20 cm from the biprism. Keep your eye just above the eye-piece and make sure that you see two images of the slit. If you do not, adjust the position of the biprism or the eye-piece by moving either of them laterally. However, you should not disturb the vertical alignment of the biprism while moving it.
7. Next, look through the eye-piece. You should see a number of vertical bright and dark fringes. **The fringes can be seen only if the slit and the edge of the biprism are exactly parallel to each other**. If you do not see sharp fringes in the field of view, narrow down the slit *S* and slightly rotate the biprism in its plane. These two adjustments should enable you to obtain sharp fringes in the field of view.
8. The next step is to **align the biprism and the eye-piece**. For this, you should move the eye-piece away from the biprism along the optical bench. While you move the eye-piece, keep looking through it to check whether or not the fringes shift to one side as a whole. If you observe a lateral shift of the fringes, it means that the line joining the slit and the central edge of the biprism is not parallel to the length of the optical bench. To remove this lateral shift, move the biprism (using the screw on the side of the upright) through a small distance transversely to the bench in a direction opposite to the direction of the shift till this lateral shift vanishes.
9. Now move the eye-piece forward and check whether the fringes become narrow without showing lateral shift. The above adjustments should be done alternately and repeatedly till a longitudinal movement of the eye-piece on the optical bench does not give rise to a side-ways shift of the whole fringe pattern.

With the above adjustments, your experimental set up is ready for making measurements of fringe width. Let us now learn to do so.

4.4.2 Measurement of Fringe Width

1. Note the pitch and calculate the least count of the micrometer of the eye-piece. Record it in Observation Table 4.1. **Consider the left extreme line**

on the pitch scale as zero. As the head of the micrometer is rotated, the head scale readings as well as pitch scale readings should increase.

2. To measure the fringe width, keep the eye-piece at a distance of about 20 cm from the biprism and then move the micrometer screw till the intersection of the cross wires falls on one of the bright fringe (Fig. 4.5). Note the pitch scale as well as head scale readings and record them in Observation Table 4.1.

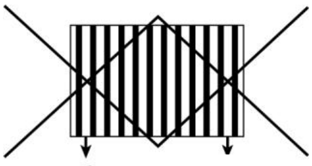


Fig. 4.5: **Enlarged view of the fringe pattern. Note how the intersection of the cross-wires is placed on any (here n^{th} and $(n+10)^{th}$ fringe) bright fringe.**

3. Next, rotate the micrometer head so that the cross-wires shift by at least 10 fringes. Record the pitch scale as well as head scale readings. **The difference gives us the width of 10 fringes.**

   (Note that there is nothing sacrosanct about the number 10; it can be 8 or 15 as well. The only important thing to remember is that the larger the difference, greater will be the accuracy of measurement and lesser the error.)

4. Repeat the above step at least three times by starting at different fringes along the pattern. Calculate the mean fringe width. Let us denote it by β_1.

5. Keeping the slit S and the biprism in the same position, move the eye-piece away by about 40 cm from the biprism. Following the steps 2 to 4 above, again determine the average value of fringe width. Let us denote it by β_2.

   Note that the purpose of measuring the fringe widths β_1 and β_2 by putting the eye-piece at two different distances D_1 and D_2, respectively from the biprism is to determine the value of (β/D) to be used in Eq. (4.23) for calculating λ. (An alternative and somewhat better method of determining (β/D) will be to vary D in steps of 5 cm and determining the corresponding values of β. Then, plot β vs. D and slope of the straight line would give the value of (β/D).)

Observation Table 4.1: Measurement of fringe width

Least count of micrometer = …… cm

Position of source slit on the optical bench = …… cm

Position of the biprism on the optical bench = …… cm

Distance between biprism and eye-piece = ... cm

Position of eye-piece	Reading of fringe		Shift	Mean	Mean
	n^{th}	$(n+10)^{th}$	10β	10β	β

SAQ 1 – Effect of number of fringes

In determining the fringe width β, the cross-wire is first placed on the n^{th} fringe and then on $(n + p)^{th}$ fringe. In your set up, you could jolly well take readings on the consecutive fringes. Would it be desirable? Record your experiences and discuss with your counsellor.

6. **To determine the distance,** ***d*** **between the virtual coherent sources**, first determine the value of focal length *f* of the convex lens by focussing a distant object on a screen.

7. Put the micrometer eye-piece at a large distance (say, more than 4*f*) from the source slit *S*. Next, insert the convex lens between the biprism and the eye-piece. Adjust the centre of the lens to be in line with the slit and eye-piece. Move the lens along the bench till sharp enlarged images of the two virtual sources are seen in the plane of the cross wires. Measure the distance $d_1 (= l_2 - l_1)$ between the images (Fig. 4.3). Move the lens, towards the eyepiece, till sharp diminished images of the two virtual sources are seen in the plane of the cross wires. Measure the distance $d_2 (= l_2' - l_1')$ between the images (Fig. 4.3). Record your readings in Observation Table 4.2.

8. Repeat step 7 at least three times and record your readings in Observation Table 4.2.

Observation Table 4.2: Measurement of separation between coherent sources

Sl. No.	Position of eye-piece (cm)	Magnified images (cm)			Diminished images (cm)			$d = \sqrt{d_1 d_2}$ (cm)
		l_1	l_2	$d_1 = l_2 - l_1$	l_1'	l_2'	$d_2 = l_2' - l_1'$	
1.								
2.								
3.								

Calculate the separation *d* between the two virtual sources using the relation

$$d = \sqrt{d_1 d_2}$$

Calculate the wavelength λ of sodium light using the relation:

$$\lambda = d\left(\frac{\beta}{D}\right)$$

Result: The wavelength of light emitted by the sodium lamp is = ………. nm

A sodium vapour lamp gives out two wavelengths, which are very close to one another. (The wavelengths are 589.0 nm and 589.6 nm.) Therefore, strictly speaking the sodium lamp does not emit monochromatic waves. How does the wavelength measured by you compare with the actual value? You can change the distance between the source slit and the biprism. How does the fringe pattern change? When the distance is very large, you should observe that fringes get crowded. Comment on the relationship between β and *D*.

If time permits and you can get to know the value of α from your Counsellor, calculate the refractive index μ and comment on the material of the biprism.

EXPERIMENT 5

WAVELENGTH OF SODDIUM LIGHT USING NEWTON'S RINGS

Structure

5.1 INTRODUCTION

From your +2 school physics curriculum, you are familiar with phenomena related to wave optics like interference, diffraction, polarisation etc. In Experiment 4, you have learnt to determine the wavelength of light using Fresnel's biprism. It is based on division of wavefront. In present experiment, you will learn to determine the wavelength of sodium light using Newton's rings method which is based on division of amplitude.

You may recall that for interference of light to occur, light waves should be monochromatic (of the same wavelength) emitted by a coherent source (i.e., have a constant phase difference), and of nearly same amplitude (intensity). Interference is normally observed (i) by division of wavefront (Young's double slit experiment, Fresnel's biprism, Llyod's mirror), or (ii) by division of amplitude (Newton's rings, Michelson interferometer). In the case of interference pattern produced by division of wavefront, the same source is used to generate two coherent sources. However, in this experiment also, two light waves are derived from a single wave. The incident wave of light in Newton's rings experiment is partially reflected from the curved glass surface of a lens and partly transmitted through an air film trapped between the lens and the glass plate kept below the lens, from which partial reflection takes place. (This partial reflection means amplitude of incident wave is being divided.) Two reflected waves superpose / interfere giving rise to bright and dark fringes in the form of concentric circles. These rings are known as **Newton's rings**.

In this experiment, you will learn to use spherometer and travelling microscope to respectively measure the radius of curvature of the plano-convex lens and the diameter of Newton's rings. You will observe that central ring is dark because a phase difference of π is introduced due to reflection from the glass plate, which is a denser medium.

Before discussing the theory and procedure of Newton's ring experiment, we state the skills that you are expected to acquire after performing this experiments.

Expected Skills

After performing this experiment, you should be able to:

- use a travelling microscope;
- use spherometer to measure the radius of curvature of a lens;
- plot a curve between D_n^2 and number of rings *n* under investigation and interpret them; and
- determine the wavelength of sodium light.

The apparatus that you will use for this experiment is listed below.

Apparatus Required

Sodium vapour lamp (source of light), a travelling microscope , smooth glass plates of 1 to 2 mm thickness , Plano-convex lens of 5 to 6 cm diameter and large radius of curvature (~100 cm), spherometer, magnifying lens and table lamp.

Before beginning the experiment you should get familiar with the apparatus used in this experiment.

5.2 KNOW YOUR APPARATUS

Travelling Microscope

Fig. 5.1: **A travelling microscope.**

Refer to Fig. 5.1, which shows a travelling microscope. It is basically a compound microscope which can be moved horizontally and vertically. It has two lenses: an eyepiece and an objective mounted at two ends of a cylindrical tube. The eyepiece has a cross wire which you may focus by sliding the eyepiece in or out. It has a steel/cast iron base fitted with levelling screws. A metallic carriage, clamped on a strong loaded bar slides with its attached vernier. The attached vernier helps to increase the accuracy of measurement. We can get an idea about this by calculating its least count. You have learnt to calculate least count of a vernier callipers in your earlier laboratory courses. Yet for completeness, we repeat the steps for your ease. Suppose that the main scale least count (minimum length it can measure) is 0.5 mm. It means that it can be used to measure lengths greater than or equal to 0.5 mm. However, once a vernier scale whose 50 divisions coincide with say 49 main scale divisions, the length of 1 vernier scale division is

$$1 \text{ Vernier Scale Division} = \text{length of } \left(\frac{49}{50}\right) \text{ Main Scale Division}$$

Hence, the least count (or vernier constant) of the instrument in the instant case has the value

$$\text{Least Count (LC)} = [1\text{MSD} - 1\,\text{VSD}] = \left[1 - \left(\frac{49}{50}\right)\right]$$

$$\times \text{ value of length of 1 Main Scale Division}$$

$$= \left(\frac{1}{50}\right) \text{X } 0.5 \text{ mm} = 0.01\text{mm or } 0.001\text{cm}$$

The length measured by such a device is given as

Length = Main Scale Reading + (Least Count) × (Vernier Scale Reading)

To ensure that you have understood the process of calculation of least count, we would like you to repeat the above exercise for a Vernier Callipers where 9 MSD coincide with 10 VSD.

Spherometer

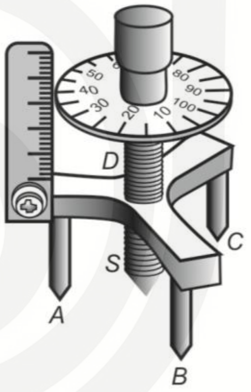


Fig. 5.2: **A spherometer.**

Refer to Fig. 5.2. It shows a spherometer. A spherometer is a mechanical device used for measuring small thickness and the radius of curvature of curved surfaces such as spherical mirrors and lenses. You may have used it in your school physics laboratory. A spherometer consists of a metallic tripod frame supported on three fixed legs (*A, B* and *C* in Fig. 5.2) of the same size. A screw passes through the centre of the tripod frame parallel to the three legs. At the centre of the tripod frame, there is a screw *S* which is parallel to the legs and which can be raised or lowered by rotating it up and down through a hole at *D*. When the screw is lowered to touch the surface on which the three legs rest, the point where screw *S* touches the surface is the centre of the equilateral triangle formed by the three legs. This point is also the centre of a circle passing through the three points marked by the legs of the spherometer. A graduated circular disc, usually with 100 equal parts is attached to the top of the screw. A small vertical scale, with graduations in millimetres, is fixed at one end of the tripod. It is referred to as the pitch scale.

The least count of a spherometer is calculated by noting the counts displaced on the main scale when the circular scale has made one complete rotation. If there are 50 marking on the circular scale and on one complete rotation, a displacement of 0.05 cm is observed on the main scale, then

$$\text{Least count of this spherometer} = \left(\frac{0.05}{50}\right) = 0.001 \text{ cm.}$$

What will be the least count if there are 100 marking on the circular scale and on one complete rotation, a displacement of 0.05 cm is observed on the main scale? You will agree that it will be 0.0005 cm.

5.3 Observing Newton's Ring

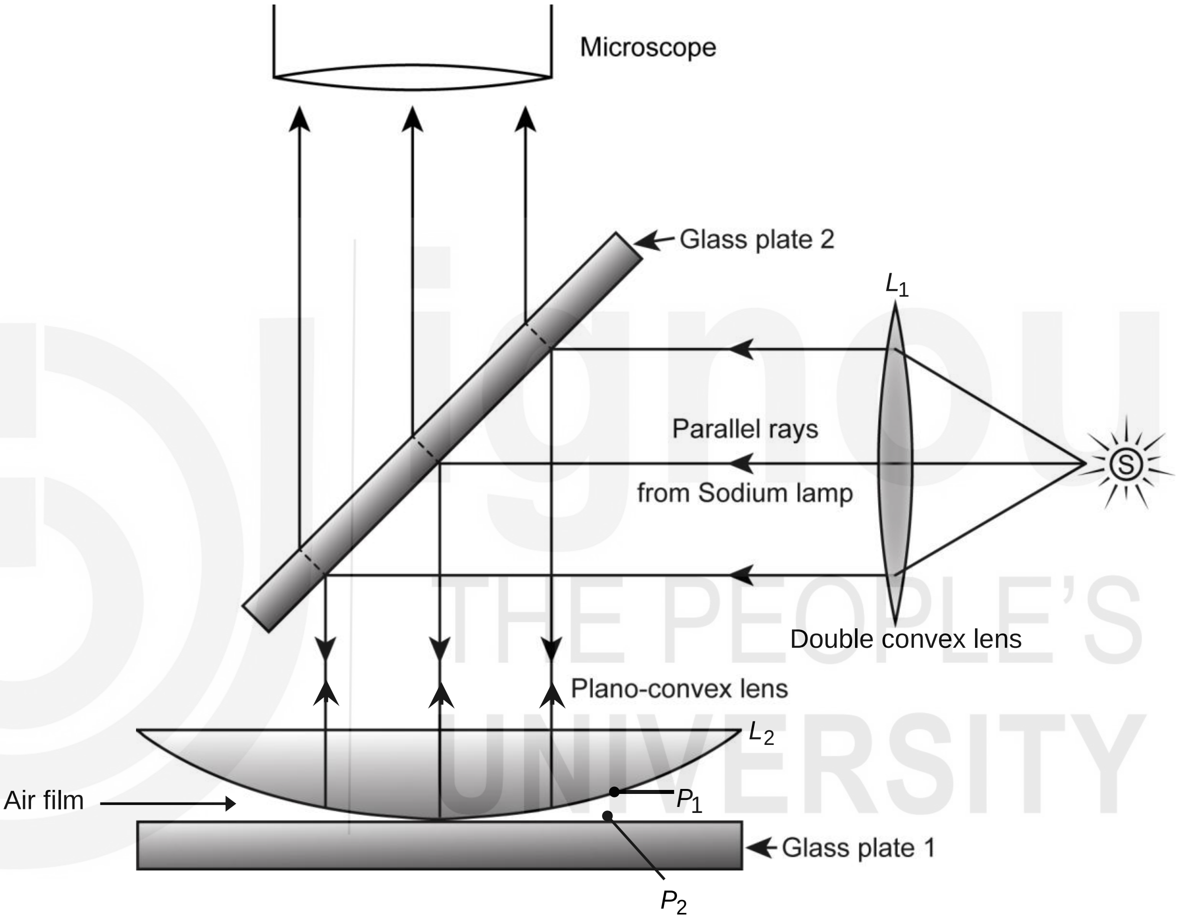


Fig. 5.3: **Schematic representation of the experimental arrangement used to observe Newton's rings.**

Refer to Fig. 5.3. It shows the experimental arrangement to observe Newton's rings. An extended source of monochromatic light such as sodium lamp is placed at the principal focus of a double-convex lens (L_1) so that a parallel beam of light reaches the glass plate 2, which is inclined at 45 degree. The glass plate 2 partially reflects the light incident on it as a parallel beam towards the air film enclosed by the surface of the plano-convex lens and the upper surface of the plane glass plate 1. This light is reflected from the bottom of the plano-convex lens (point P_1) and the top of the glass plate 1 (point P_2). These two light waves have a path difference between them due to the thickness of air film between the points P_1 and P_2. They interfere leading to formation of Newton's rings, which are circular and can be seen with unaided eye. However, for making measurements, we have to use a travelling microscope.

5.3.1 Theory

To obtain an expression for the radii of Newton's rings and relate these to the wavelength of light used, we note that thickness of the air film enclosed between the lens and glass plate increases as we move away from their point of contact, *O,* (Fig. 5.4). However, since plano-convex lens is a part of a spherical glass ball of large radius of curvature, say *R*, the air gap for all points at a distance ' r_n' from the point of contact, would be the same. Now suppose that thickness of the air film where *n*th dark ring is formed is *d* and corresponds to point *M* and the radius of the dark ring is denoted by r_n.

The radius of curvature of the curved surface of the lens is *R*. By invoking the property of a circle, we can say that *L*OME = 90°. In Fig. 5.4, *N* is the foot of the perpendicular drawn on the hypotenuse of a right angled triangle from the vertex containing the right angle. Using the property of similarity of triangles *EMN* and *EMO*, we can write

$$(MN)^2 = EN \times ON \qquad (5.1a)$$

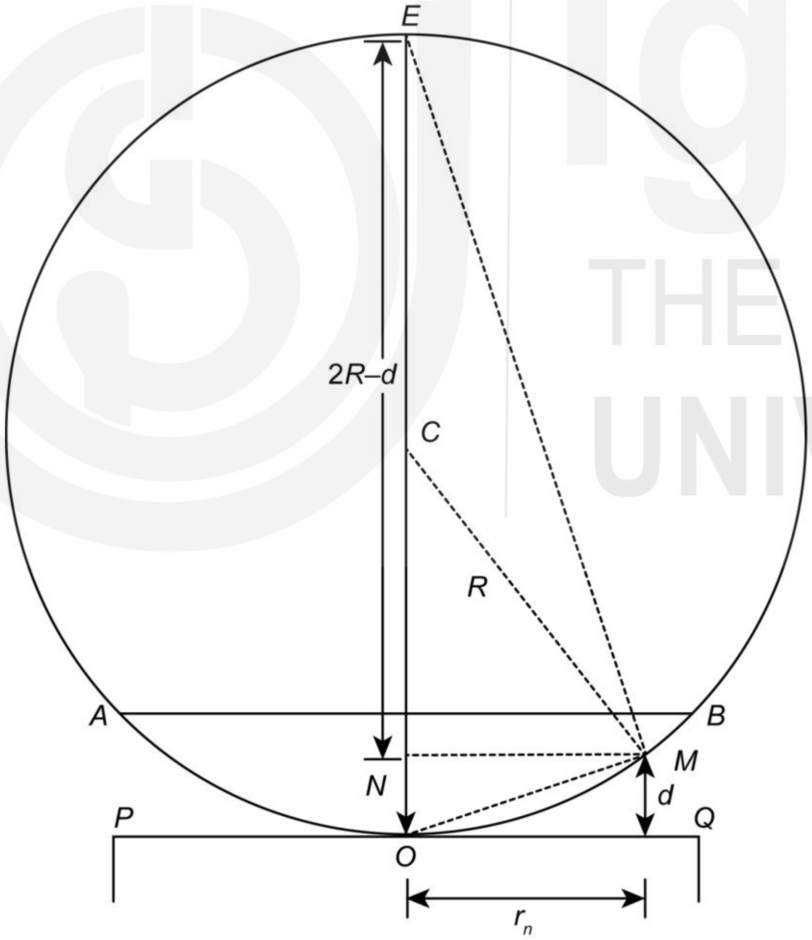


Fig. 5.4: **Geometry of the Newton's ring experiment.**

Here we note that *EN* = (2*R* – *ON*). Therefore, we can write

$$(MN)^2 = (2R - ON) \times ON \qquad (5.1b)$$

On substituting *MN* = r_n and *ON* = *d* in Eq. (5.1b), we get

$$r_n^2 = (2R - d)\,d \tag{5.1c}$$

The radius of curvature of the lens in a typical arrangement used to obtain Newton's ring is significantly greater than d (R>>d), R=1.0 m and $d \le 10^{-5}$ m. physically speaking, the radius of curvature of the lens is far greater than the thickness of air trapped between the two glass surfaces. In this approximation, the expression given in Eq. (5.1c) simplifies to

$$r_n^2 = 2Rd \tag{5.2a}$$

The subscript 'n' has been added to imply that we are talking about the diameter of the n^{th} fringe.

We can rewrite Eq. (5.2a) as

$$2d = \frac{r_n^2}{R} \tag{5.2b}$$

Note that the interference takes place between reflected waves and the dark fringes are formed when the path-difference is an integral multiple of the wavelength (or even integral of $\lambda/2$). Mathematically, we express it as $2\mu d\cos\theta = n\lambda$. For air, $\mu = 1$ and since light is made to fall normally on the lens, $\theta = 0.$ Hence, this relation simplifies to

$$2d = n\lambda$$

On combining this result with Eq. (5.2b), we get

$$r_n = \sqrt{n\lambda R} \tag{5.3}$$

Note that for $n = 0,\ \ r_n = 0,$ i.e. the central fringe would be dark. However, the central fringe is circular. This makes it impossible to make an accurate judgement of the centre and in turn the measurement of the *radius* of the fringe. So, from the practical point of view, you should measure the *diameter* of the dark fringes. It is related to the wavelength as

$$D_n = 2\sqrt{n\lambda R}$$

For convenience in calculations, we do away with the square root and rewrite the relation between diameter of the dark rings and the wavelength as

$$\mathrm{D}_n^2 = 4n\lambda R \tag{5.4}$$

where the subscript 'n' implies that we are considering the diameter of the 'n^{th}' fringe/ring.

Before proceeding further, you should answer the following SAQ.

SAQ 1 - Refractive index of a liquid

Can Newton's ring experiment be used to determine the refractive index of a liquid? If yes, suggest the modification required in the apparatus.

You are now ready to perform the experiment.

5.3.2 Procedure

1. Calculate the least count of travelling microscope and that of the spherometer and record these in Observation Tables 5.1 and 5.2.
2. Clean the surfaces of the lens as well as the glass plates well using lint free cloth or tissue paper. Do not touch the glass plates and lens surfaces at any time. Always hold them by their sides/edges. Make sure that glass plates are smooth and free from scratches. You must make sure that there are no finger prints visible on the glass surfaces. Place the plano-convex lens on the glass plate. Set the plate (plate 2) at 45° to the horizontal as shown in Fig. 5.3.

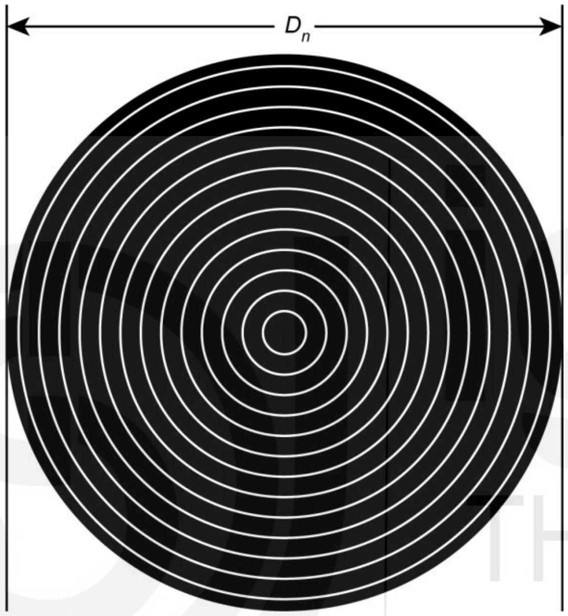


Fig. 5.5: **Circular fringes expected in Newton's ring experiment.**

3. Place this arrangement in front of a sodium vapour lamp. Next make sure that a beam of parallel rays of sodium light from the lamp falls on plate 2. This can be easily done by placing the Newton's ring arrangement 20-30 cm away from the extended source. Note that you have to get an extended source not a point source or slit. Plate 2 should be at an angle of 45° with respect to the horizon so that a small fraction of light is reflected along the normal on to the lens-Plate 1 arrangement.
4. Position yourself near the location of "Microscope" shown in Fig. 5.3 so that you can check visibility of Newton's rings. Make sure that these are distinctly visible. In case you are unable to see the fringes distinctly, check your set up again. If the lens-Plate 1 arrangement is fine, slowly move Plate 2 to confirm 45° slant.
5. Set the microscope and focus it to get clear image of the rings. If you find it difficult to focus the rings, place a tiny piece of paper on top of the lens and focus the microscope on the paper. Gently blow the paper away and slowly adjust focus to obtain sharp image of the rings. (In case, the rings are still not clear, you may seek the help of your counsellor.)

6. Set the microscope such that when the cross-wire is moved to left or right (say, left hand side), it moves along the diameter of the ring (through the centre) rather than along a chord of the circles.

7. Now, beginning from the central dark spot of the ring pattern, start counting either bright or dark rings 1, 2, 3 ... till 11th ring either in the left or the right side with the help of the cross-wire.

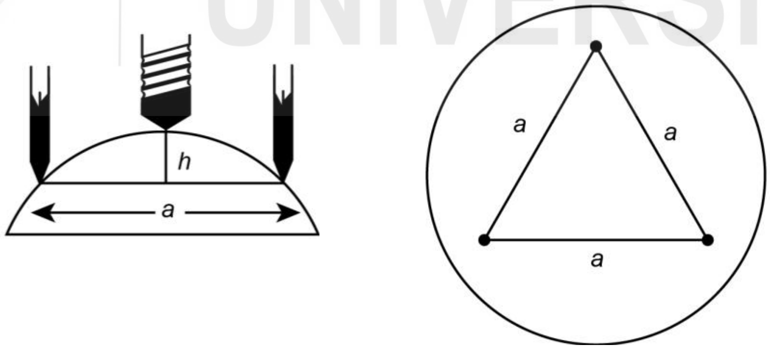
8. Now return back by moving the travelling microscope side screw. Set the cross-wire on the 10th ring on LHS. Note down the main scale and vernier scale readings for the 10th ring on LHS.

9. Move the side screw of the microscope and set the cross-wire on 9th ring and take readings. Similarly, take observations for 8th, 7th ...till 1st ring on LHS.

10. Now move in the same direction and set the cross-wire on 1st ring on RHS. Note down the readings. Repeat the process for 2nd, 3rd ...till 10th ring on the RHS. Record all your readings in Observation Table 5.1. The difference of the readings of LHS and RHS will give diameter of the 10th, 9th, 8th ... 1st ring under observation.

11. It is important to note that all observations should be taken with movement along one direction only, i.e., from left to right or from right to left.

12. Remove the plano-convex lens and place it on a plane clean surface with its plane surface facing down (Fig. 5.6a). With the help of the spherometer, you now need to measure the radius of curvature of the lens. To do so, first level the spherometer. That is, place it on a flat glass plate and rotate the spherometer screw till the centre tip and the three tripod legs touch the glass surface. This in a way is the zero level reading. Record it in Observation Table 5.2.



(a) (b)

Fig. 5.6: **Determination of the radius of curvature of lens using a spherometer.**

13. Now rotate the central screw of the spherometer anticlockwise and bring it up by about one centimetre.

14. Place the spherometer on the curved surface of the lens. Rotate the screw clockwise so that the tip moves downward. The moment it touches the curved surface along with the three tripod legs (see Fig 5.6a), stop rotating it. Record your readings in Observation Table 5.2.

15. The difference between these readings (step 12 and 14) gives the thickness (*h*) of the portion of the sphere cut off by the plane passing through the three feet.

16. You should always move the micrometer screws of the travelling microscope as well as the spherometer slowly and in one direction only to avoid backlash error.

17. The three tips of the tripod forms an equilateral triangle and to have a measure of the distance *a* between the legs, press the spherometer on a paper and measure distances between the pinholes left behind by the tripod legs edges (Fig. 5.6b). The radius of curvature can be easily calculated using the relation

$$R = \left(\frac{a^2 + 3h^2}{6h}\right) \tag{5.6}$$

18. Plot a graph between the number of rings (*n*) and the corresponding square of the diameter (D_n^2) (Fig 5.7) which is a straight line passing through the origin. Calculate the slope of this line and use it in Eq. (5.4) to determine the wavelength of sodium light.

Observation Table 5.1: Determination of diameter of Newton's rings **using a travelling microscope**

Least Count of the travelling microscope = ...

Order of Ring	**Reading of LHS edge**			**Reading of RHS edge**			$D_n =$ **(*a*) − (*b*) (in** m**)**	D_n^2 **(in** m^2**)**
	Main Scale	**Vernier Scale**	**Total (*a*)**	**Main Scale**	**Vernier Scale**	**Total (*b*)**		
20								
18								
16								
14								
12								
10								
8								
6								
4								
2								

Observation Table 5.2: Determination of *h* using a spherometer

Least Count of the spherometer = ...

S.No	On Glass Plate (Zero level)			On lens Curved Surface			$h = (b) - (a)$
	Main Scale	Circular Scale	Total (a)	Main Scale	Circular Scale	Total (b)	
1.							
2.							
3.							
4.							
5.							

Mean h = ... cm

h = ... m

5.4 Calculations

1. Calculate the radius of curvature of the plano-convex lens R using the data recorded in Observation Table 5.2 in Eq. (5.6).
2. A plot of the order of the ring n along x-axis and the corresponding diameter squared (D_n^2) along the y-axis should be a straight line (Fig. 5.7) passing through the origin. The slope of the straight line along with R gives the value of wavelength of the sodium light by the relation [Eq. (5.4)]:

$$\lambda = \left(\frac{\text{slope}}{4R}\right)$$

where 'R' is the radius of curvature of the lens. .

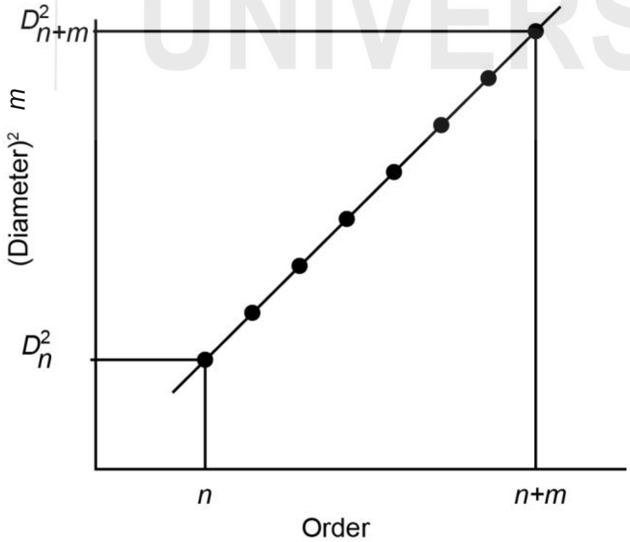


Fig. 5.7: **Expected graph between (diameter of the ring D)^2 versus number of rings.**

Result: Value of R = ... m

The wavelength of the sodium light is = ... nm

EXPERIMENT 6

WAVELENGTH OF SODDIUM / MERCURY LIGHT USING A PLANE DIFFRACTION GRATING

Structure

6.1 INTRODUCTION

In this laboratory course, you have so far worked in situations dealing with refraction of light, interference of light and polarisation of light. Now you will investigate another phenomenon associated with the wave nature of light: diffraction. In our day to day life, we observe that light casts shadows of objects. This implies that light rays travel along straight lines. However, it has also been observed that light bends around corners if the size of the obstacle or aperture kept in the path of light is comparable with the wavelength of the light. This bending of light from the straight line path is called diffraction. The phenomenon of diffraction was explained by Fraunhofer as well as by Fresnel on the basis of the wave theory of light.

You have studied diffraction of light in the fourth semester course entitled Waves and Optics (BPHCT-137). You may recall that the extent of diffraction, that is, the angle of diffraction, depends on the wavelength of the light used. In this experiment, you will use this fact to determine the wavelength of sodium and/or mercury light. To perform this experiment, you will use a spectrometer and a diffraction grating. You have learnt about spectrometer and how to use it in Experiment 1 of this course. We hope you will be comfortable working with it now. Further, you also learnt in BPHCT-137 that diffraction grating acts as a collection of a large number of equally spaced parallel slits. This optical device is very useful for determining the wavelength of spectral lines emitted by a substance/source.

In the present experiment, you will learn to use spectrometer and a diffraction grating to determine the wavelength of sodium or mercury light.

Expected Skills

After performing this experiment, you should be able to:

- set up the spectrometer for observing spectrum and making measurements;
- set-up grating for normal incidence with respect to incident beam of light;
- measure the diffraction angle; and
- determine the wavelength of sodium/mercury light.

You will require the following apparatus for this experiment.

Apparatus Required

Spectrometer, plane diffraction grating, spirit level, sodium lamp (or mercury vapour lamp, as the case may be), and magnifying glass.

6.2 DIFFRACTION OF LIGHT

From your school physics, you know that diffraction of light is the phenomenon of bending of light around corners of an obstacle or aperture placed in the path of light. On account of this bending, light enters into the geometrical shadow region also. You may recall the essential condition for diffraction to be observed. That is, the dimensions of the obstacle or aperture should be comparable with the wavelength of light. The diffraction phenomenon is explained on the basis of the wave theory of light.

As you learnt in BPHCT-137, the diffraction phenomena are divided into the following two classes depending upon the relative positions of the source, diffracting object and the observation screen:

i) **Fresnel diffraction**

When the source of light or the screen on which diffraction pattern is observed or both are at a finite distance from the obstacle causing the diffraction, Fresnel diffraction occurs. In this case, no lenses are used. The wavefronts are spherical or cylindrical.

ii) **Fraunhofer diffraction**

In Fraunhofer diffraction, the source of light and the screen (or telescope used to view the diffraction pattern) is placed at infinite distance from the obstacle. But, in practice, no equipment can be placed at infinity. In laboratory, therefore, this condition is obtained by using lenses. You may also recall from your BPHCT 137 that, while superposition of waves is the basic mechanism responsible for interference as well as diffraction of light, there are differences in details. In interference phenomenon, superposition of two separate wavefronts originating from two coherent sources takes place, whereas in diffraction phenomenon, superposition of secondary wavelets originating from two different parts of the same wavefront occurs. Further, interference and diffraction patterns also differ from one another in respect of brightness of fringes and the fringe width.

Having recapitulated basics of diffraction phenomenon, let us now learn about diffraction grating.

6.2.1 Diffraction Grating

Diffraction grating is an arrangement of a large number of equidistant, narrow rectangular slits of equal width placed side by side parallel to one another. A practical grating consists of a well polished glass or metal surface upon which a large number of fine, equidistant parallel lines are ruled with the help of a fine diamond point or similar device. The number of the ruled lines per inch may vary from 7500 to 15000 and these lines are opaque to light while the clear/transparent spaces in-between the lines diffract light.

The original ruled gratings are very costly. So, nowadays, cheaper gratings are available for use in laboratories in the form of celluloid casting called Replicas. In the physics laboratory, you will be using such a replica (also called Students' grating) to perform this experiment.

There are mainly two types of diffraction gratings:

i) Transmission grating which has rulings on transparent glass or sheets.

ii) Reflection grating which has rulings on a metal or some other reflecting surface.

In the present experiment, you will use a transmission grating. Let us now learn about the theoretical basis of its working.

Refer to Fig. 6.1 which shows the cross-sectional view of a plane transmission grating having say, *N* slits (clear spaces like *AB*) perpendicular to the plane of paper. Note that the width of every slit is same and the width of the opaque space such as *BC* between any two consecutive slits is also the same. (However, the width of opaque space may not be the same as transparent space.) In view of the fact that the width of a slit is comparable to the wavelength of light, each slit in the grating sends out a diffracted beam and these diffracted beams then superpose or interfere with one another to produce a resultant pattern on the observation screen *S*. When a beam of monochromatic light of wavelength λ is incident on a grating, it gets diffracted by each slit in different directions. In such a situation, light coming out of the slits superpose with each other leading to the variation in intensities manifested as formation of dark and bright bands on the screen *S.* The intensity distribution in the diffraction pattern on the screen is such that there are bright and dark fringes on both sides of a central bright fringe (Fig. 6.1). The bright and dark bands/fringes correspond to the maxima and minima in intensity and depend on the path difference between the two superposing waves.

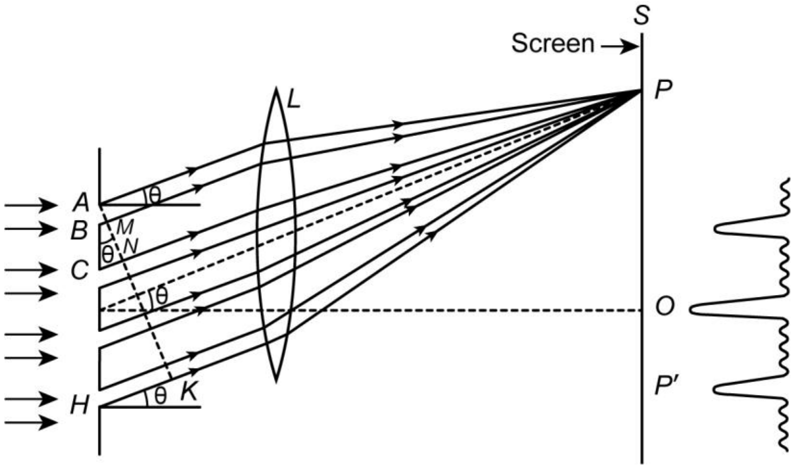


Fig. 6.1: **Diffraction due to a transmission grating.**

Let us consider that the rays are diffracted at an angle θ with the normal. You may ask: Whether the rays diffracted from two corresponding points *A* and *C* at an angle θ will produce constructive interference or destructive interference at point *P*? This will be determined by the relation between the path difference between the two rays and wavelength of the light. To determine the path difference, we draw a normal *AK* from point *A*. Then, *CN* denotes the path difference between the rays diffracted from the two corresponding points *A* and *C*. From the geometry of Fig. 6.1, we can express the path difference as

$$CN = AC \sin\theta \qquad (6.1)$$

If '*a*' denotes the width of the transparent space, *AB* and '*b*' the width of opaque space *BC*, then *AC* = (*a* + *b*). Note that (*a* + *b*) is called **grating element** or **grating constant** and its value is

$$(a + b) = 1/N \qquad (6.2)$$

If *N* be the number of lines per inch, then the

$$\text{Grating element, } (a+b) = \left(\frac{2.54}{N}\right)\text{cm} \qquad (6.3)$$

In terms of the grating element, we can write Eq. (6.1) as

$$CN = (a + b) \sin\theta \qquad (6.4)$$

You may recall from Unit 6 of BPHCT 137 that, if the path difference is an even multiple of λ/2, the rays from *A* and *C* will produce constructive interference at point *P* and it will correspond to bright fringe (called, maxima). On the other hand, if the path difference is an odd multiple of λ/2, then the rays from *A* and *C* will produce destructive interference at point *P* and it will correspond to *dark* fringe (called, minima).

Thus, the conditions for obtaining diffraction maxima and minima on the screen are

$$(a+b)\sin\theta = \pm n\lambda, \qquad \text{for a maximum} \qquad (6.5)$$

and

$$(a+b)\sin\theta = \pm(2n+1)\frac{\lambda}{2}, \quad \text{for a minimum} \qquad (6.6)$$

where n = 0, 1, 2, 3, … represents the order of diffraction. Note that, when the path difference is zero, i.e., all the rays reach a point (point *O* in Fig. 6.1) on the screen in phase and we get the central bright maximum. All other higher order maxima on the either side of the central maximum have gradually diminishing intensities.

Now the question arises: What is the maximum number of orders of diffraction produced by a given grating? Let us discover answer to this question. The condition for maxima produced by a grating is [Eq. (6.5)]:

$$(a+b)\sin\theta = n\lambda$$

$$\therefore \quad n = \frac{(a+b)\sin\theta}{\lambda} \qquad (6.7)$$

The maximum value of the angle of diffraction (θ) is 90°. Hence, the maximum possible order is given by

$$n_{\text{max}} = \frac{(a+b)\sin 90^\circ}{\lambda} = \frac{(a+b)}{\lambda} \qquad (6.8)$$

Having discussed the conditions of maxima and minima as well as order of diffraction pattern that can be obtained with a given grating, you are now ready to perform the experiment. Since you have to determine the wavelength of light emitted by a given source (sodium or mercury), you will use Eq. (6.5) as the working formula:

$$(a+b)\sin\theta_n = n\lambda$$

$$\therefore \quad \lambda = \frac{(a+b)\sin\theta_n}{n}$$

where (a + b) = grating element $= \frac{1}{N}$, n is order of diffraction (n = 1, 2, 3, …) and θ_n is angle of diffraction corresponding to the n^{th} order.

6.3 PROCEDURE

The procedure for doing this experiment broadly includes the following three major steps:

- Adjustment of the spectrometer.
- Adjustment of the grating for normal incidence.
- Measuring the angle of diffraction.

6.3.1 Adjustment of the Spectrometer

You have learnt how to set up (or adjust) the spectrometer in Experiment 1 of this course. You may recall that adjustment of the spectrometer includes its levelling, adjusting the slit and adjustment of collimator and telescope for parallel rays using Schuster's method. You should refer to Sec. 1.3.1 of

Experiment 1 and adjust the spectrometer. (You do not have to adjust the placement of prism because, in this experiment, you will use a diffraction grating.)

6.3.2 Adjustment of the Grating for Normal Incidence

The grating should be placed/mounted vertically on the prism table of the spectrometer so that the incident rays are perpendicular to gratings plane. Follow the steps given below for adjusting the grating for normal incidence:

1. First, bring the telescope (T) in line with collimator (C) to obtain a sharp image of the slit coincident with the vertical cross wire **without placing the grating over the prism table**. Take the reading of either vernier of the spectrometer.
2. Rotate the telescope through 90° (by adding or subtracting 90° from the reading noted in step 1 above) and fix it.

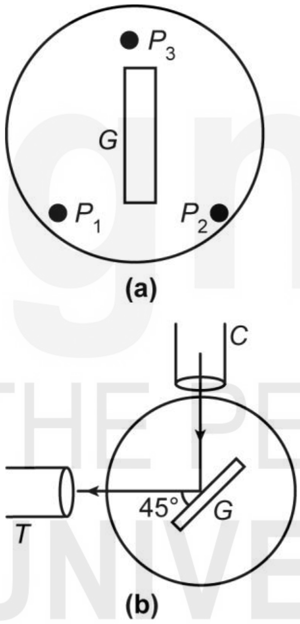


Fig. 6.2: **Adjustment of grating on the spectrometer.**

3. Place the grating (G), mounted in its holder, on the prism table vertically such that it is almost at the centre of the prism table and the grating plane is normal to the line joining the levelling screws P_1 and P_2 of the prism table (Fig. 6.2a).
4. Turn the prism table slowly until an image of the slit is formed on the cross wires of the telescope by reflection from the unruled surface of the grating. (In general, the details of the grating are written on the ruled side of the grating that helps in distinguishing between its ruled and unruled surfaces. Moreover, image of the slit in the telescope due to reflection from the unruled surface is brighter than that obtained from the ruled surface.)
5. Rotate one of the screws, P_1 or P_2 till the centre of the image coincides with the junction of the cross wires. This ensures that the grating has become vertical. In case the slit is not coinciding with the vertical cross wire throughout its length, then adjust it with the help of the third screw P_3 without disturbing the other two screws. Note from Fig. 6.2 that, in this

condition, the grating is at 45° with respect to the incident light. Note down the reading of the prism table.

6. Rotate the prism table through 45° in such a direction that the ruled surface of the grating faces the telescope. In this position, the grating plane is perfectly normal to the incident light coming from the collimator. Clamp the prism table in this position. (Rotate the telescope by 90° to face the collimator. See through the telescope and you should observe that the direct ray image of the slit coincides with the cross wire.)

With the above adjustment, the grating is adjusted for normal incidence.

6.3.3 Measurement of the Angle of Diffraction

To measure the angle of diffraction, follow the steps given below:

1. When the telescope and collimator are aligned along a line, you should observe a fringe pattern with a central bright fringe. Rotate the telescope slowly in either side of this central fringe till you observe the image of the slit. This is first order spectrum indicated by *OA* position in Fig 6.3.

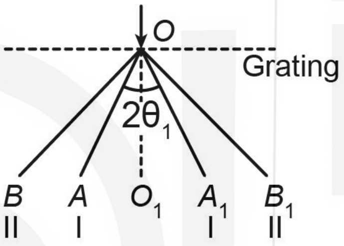


Fig. 6.3: **Measurement of diffraction angle.**

2. If the resolving power of the grating is sufficiently high, you will observe two distinct images of the slit in the first order spectrum for sodium lines D_1 and D_2 corresponding to the wavelengths 5890 Å and 5896 Å. Fix the vertical cross wire in between the two closely spaced images and note down the readings on both the verniers V_1 and V_2 of the spectrometer in Observation table 6.1. (In case the two slit images (lines) are not distinctly separated, bring the vertical cross wire on the centre of the single (but, little broad) line and note the readings of verniers for the first order on the left of the central bright fringe.)
3. Rotate the telescope on the other side and coincide the cross wire with the first order spectrum indicated by OA_1 position in Fig. 6.3. Note the readings of the verniers for first order on right of the central bright fringe in Observation Table 6.1. The difference of the corresponding readings gives the values of $2\theta_1$ for the first order spectrum.
4. Rotate the telescope further on either side of the central bright fringe and find the second order spectrum. You will observe that the intensity of the spectral lines is comparatively less than that in the first order spectrum. Note the readings and repeat the same for other side. The difference of two corresponding readings will give the value of $2\theta_2$ for second order spectrum.
5. Repeat steps 1 to 4 two more times and determine the mean values of θ for different orders of spectrum.

Observations

Least count (vernier constant) of the spectrometer =

No. of lines per inch on the grating N = ………

Grating element $(a+b) = \dfrac{2.54}{N} =$ ....cm.

Observation Table 6.1: Measurement of angle of diffraction

Sl. No.	Order of spectrum	Vernier	1st Position of Telescope			2nd Position of Telescope			Difference between 1st and 2nd Positions (=2θ)	θ	Mean θ
			MSR	VSR	Total	MSR	VSR	Total			
1	1st order	V_1									$\theta_1 =$
2		V_2									
3		…									
1	2nd order	V_1									$\theta_2 =$
2		V_2									
3		…									

Calculation for determining the wavelength

For 1st order spectrum,

$$(a+b)\sin\theta_n = n\lambda$$

From the observation table 6.1, for the first order spectrum (n = 1) $\theta_1 =$ ....°

So, $\lambda = (a+b)\sin\theta_1. =$ ....m

For 2nd order spectrum (n = 2), $\theta_2 =$ ....°

$\lambda = (a+b)\sin\theta_2 =$ ....m

Mean $\lambda =$ ....m

Result

The calculated value of wavelength of sodium light = ……………… m

Standard value = ………………. m

% error = ………………

[**Note:** If you are given mercury lamp instead of sodium lamp in your laboratory arrangement, the wavelength can be determined using a diffraction grating following the same procedure as described above. However, you should be mindful of the fact that the light (white) from mercury lamp comprises lights of different colours (having different wavelengths). Since the diffraction angle is a function of the wavelength, the maxima of different orders are obtained in the directions (θ’s) satisfying the relation $(a+b)\sin\theta = \pm n\lambda$. Therefore, when mercury light is used, we observe several coloured lines corresponding to the emission lines of mercury in each order spectrum. Thus, you can determine the value of wavelength of the different emission lines of mercury by measuring the angle of diffraction for a particular line (colour) or for several lines.]

EXPERIMENT 7

DISPERSIVE POWER OF A PRISM

Structure

7.1 INTRODUCTION

You have studied dispersion of light in your school physics. Recall that dispersion of light is a phenomenon in which white light (say, from the Sun or mercury lamp), incident on the refracting surface of a prism, splits into its constituent colours. The dispersion of white light is caused due to refraction of different wavelengths at different angles in the prism. That is, light of different colours, each having a characteristic wavelength, gets refracted at different angles leading to break up of white light into seven colours. The rainbow we observe in the rainy season is an example of dispersion of light in nature. The rainbow is produced when sun light is refracted by tiny water droplets suspended in the atmosphere in the rainy season.

In your +2 physics, you have learnt that dispersion is said to be normal, if

1. Order of the principal colours follows the acronym VIBGYOR (Violet, Indigo, Blue, Green, Yellow, Orange, Red) in the visible region; and

2. Violet light suffers maximum deviation and red light undergoes the minimum deviation.

We can understand these observed facts about dispersion by noting that different substances have different refractive indices. And refractive index is defined as the ratio of speed of light in free space to that in a material medium. It means that dispersion is intimately connected with speed of light in a material medium and its variation with wavelength.

In Experiment 1, you learnt to determine the refractive index of the material of a prism using sodium light. To determine the refractive index, you measured the angle of minimum deviation for the monochromatic light incident on the prism. In the present experiment, you will learn to determine the dispersive power of the material a prism. The dispersive power of a prism refers to its ability to separate two lights of different wavelengths. For this purpose, you will need to use a spectrometer to measure the angle of the given prism and the angles of minimum deviation for lights of different wavelengths incident on the prism. Therefore, you will be performing Experiment 1 for different wavelengths (colours).

Expected Skills

After performing this experiment, you should be able to:

- set up the spectrometer to determine the angle of the prism;
- determine the angles of minimum deviation of a prism for lights of different wavelengths;
- calculate refractive index of the material of the prism for red, yellow and violet lights; and
- calculate the dispersive power of the material of the prism.

You will require the following apparatus for this experiment.

Apparatus Required

Sodium (Na) lamp / Mercury (Hg) lamp, prism, spectrometer (collimator, prism table, telescope), magnifying glass, spirit level, torch, table lamp, scale, cleansing cloth.

7.2 DISPERSION OF LIGHT

You know from school physics that when a beam of light passes from one medium to another, it deviates from its rectilinear path. This phenomenon is called refraction. The refraction of light is associated with the change in speed and wavelength of light as it passes from one medium to another. Recall that speed of a wave is given as $v = f\lambda$ .Since frequency of light *f*, remains unchanged when it travels from one medium to another, the change in speed leads to change in wavelength. You know that the speed of light in vacuum is maximum and its speed reduces when it enters any material media from air.

When white light propagating in air enters a medium such as glass, its speed decreases to about 75 percent of its speed in air. In other materials, the decrease can be even more. The speed of light in air is about 99.97 percent of its speed in vacuum. The extent by which the speed of light is reduced in a medium is a characteristic of the medium.

(The speed of light in air is taken equal to its speed in vacuum.) For example, the speed of light in glass reduces by about 25 percent. This reduction in speed of light causes refraction of light whenever it enters from air to a material medium or from one material medium (say, water) to another (say, glass).

You may now ask: How much does a beam of light of given frequency deviate from its rectilinear path after entering a transparent medium? The extent of refraction of light in a medium is a characteristic of the medium under consideration. This characteristic of the medium is signified by its **refractive index**, μ. As you learnt in Experiment 1, the refractive index of a medium is defined as

$$\mu = \frac{c}{v}$$

where c is the speed of light in vacuum and v is its speed in the medium. Note that the refractive index of a medium is always defined with respect to another medium from which light enters. In the instant case, we have defined the refractive index of a transparent medium (such as, glass or plastic) with respect to air (the medium of incidence).

In terms of microscopic parameters, the refractive index of a material is given as

Refractive index

$$= \sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}}$$

where ε_0 and ε are the permittivity of free space (or vacuum) and material medium respectively and μ_0 and μ are the permeability of free space (or vacuum) and material medium respectively.

Proceeding further, recall that white light from the Sun comprises seven colours, each having a characteristic frequency (or wavelength). When a beam of sun light is incident on a prism, it splits into constituent colours of different wavelengths. This phenomenon is called dispersion of light. The dispersion of white light by a prism is shown in Fig. 7.1.

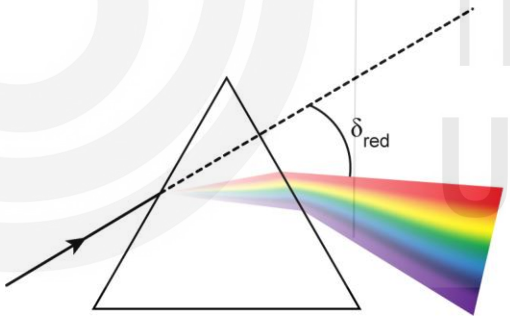


Fig. 7.1: **Dispersion of white light by a prism.**

The dispersion of composite light is attributed to the fact that refractive index of the material of the prism is different for different colors. You may note from Fig. 7.1 that the extent of refraction of light increases from red to violet; that is, higher the wavelength, smaller is refraction. In other words, higher the wavelength, smaller is the refractive index. It means that, in refraction through a prism, the angle of deviation for the red light is smaller than that for the violet light.

7.2.1 Dispersive Power of a Prism

The commonly used prisms in physics laboratory are made of either flint or crown glass. These have different refractive indices for a given wavelength. What do you understand by this? It means that the extent of dispersion of white light by prisms made of flint and crown glasses will be different. Further, from Table 7.1 you may note that refractive indices of the flint glass are higher than those of crown glass for lights of different colours (wavelengths). It implies that light of all colours will be refracted more by flint glass than by crown glass.

Table 7.1: Refractive indices for some representative wavelengths

Colour of Light	Wavelength (nm)	Crown Glass	Flint Glass
Red	656.3	1.515	1.622
Yellow	589.3	1.517	1.627
Blue	486.1	1.523	1.639
Violet	396.9	1.533	1.663

The dependence of the dispersion of light on the material of a prism is represented by a quantity called **dispersive power.** It is defined as the power of a transparent medium to separate different colours of light due to refraction. Mathematically, the dispersive power is represented as a ratio of the difference between the refractive indices corresponding to two widely different wavelengths and the refractive index of an intermediate wavelength. For white light, the red and violet lights are taken as two widely different wavelengths and yellow light is taken as intermediate wavelength. Alternately, we can also take the average of the refractive indices corresponding to red and violet lights as refractive index of intermediate wavelength.

To obtain the mathematical expression for dispersive power, we recall from Experiment 1 that refractive index of the material of a prism is given as [Eq. (1.11)]

$$\mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\left(\frac{A}{2}\right)} \tag{7.1}$$

where A is the angle of prism and δ_m is the angle of minimum deviation (which is different for different colours).

In small angle approximation, we can take, $\sin\theta \approx \theta$. Using this result in Eq. (7.1), we obtain

$$\mu = \frac{\frac{A+\delta_m}{2}}{\frac{A}{2}} = \frac{A+\delta_m}{A} \tag{7.2}$$

Eq. (7.2) can be rearranged and written as

$$A(\mu - 1) = \delta_m \tag{7.3}$$

We know that for different colours, we will have different values of refractive indices of the prism. If we consider two extreme wavelengths of the visible light spectrum, i.e. violet and red light, we will get the following expressions based on Eq. (7.3)

$$A(\mu_{\text{violet}} - 1) = \delta_{m(\text{violet})} \tag{7.4}$$

$$A(\mu_{\text{red}} - 1) = \delta_{m(\text{red})} \tag{7.5}$$

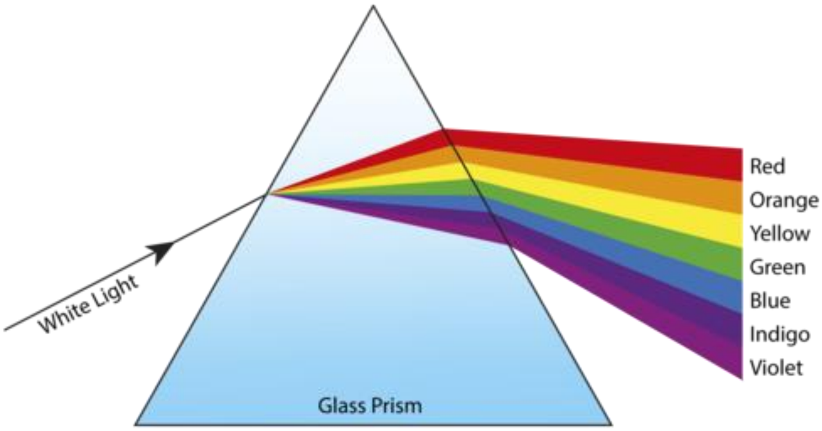


Fig. 7.2: **Angular dispersion of a prism. (**Source: Jibin 1840404, CC BY-SA 4.0; https://commons.wikimedia.org/wiki/File:Dispersions.png**)**

The difference between the angles of minimum deviation for these two colours is called **angle of dispersion** (or **angular dispersion**) (. Since the violet light is refracted more than the red light, the expression for the angle of dispersion is obtained by subtracting Eq. (7.5) from Eq. (7.4.) This gives

$$\text{Angle of Dispersion} = \delta_{m(\text{violet})} - \delta_{m(\text{red})} = A(\mu_{\text{violet}} - \mu_{\text{red}}) \tag{7.6}$$

To obtain the average refraction of white light, we take the angle of minimum deviation for yellow light. Then Eq. (7.3) can be written as

$$A(\mu_{\text{yellow}} - 1) = \delta_{m(\text{yellow})} \tag{7.7}$$

From the definition of the dispersive power, ω, given above, we can express it as the ratio of the angle of dispersion to the angle of dispersion for yellow light:

$$\omega = \frac{A(\mu_{\text{violet}} - \mu_{\text{red}})}{A(\mu_{\text{yellow}} - 1)}$$

or,

$$\omega = \frac{(\mu_{\text{violet}} - \mu_{\text{red}})}{(\mu_{\text{yellow}} - 1)} \tag{7.8}$$

Eq. (7.8) is the working formula for this experiment. So, to determine the dispersive power of the material of the prism, you need to calculate the refractive indices of the prism for violet, red and yellow lights. You can easily do so by determining the angle of the prism and the angles of minimum deviation for each of these colours using a spectrometer. Then, using Eq. (7.8) you can calculate the dispersive power of the material of the prism.

7.3 PROCEDURE

To perform this experiment, you have to (i) set up the spectrometer, (ii) measure the angle of the prism, and (iii) measure the angle of minimum deviation for violet, red and yellow colour lights. The steps for setting-up spectrometer and taking these measurements are given below.

7.3.1 Setting up the Spectrometer

From Experiment 1, you will recall that for taking any measurement using a spectrometer, first we need to level it using screws given at the base, level the prism table using spirit level, and align the collimator and the telescope collinearly.

You now know that a spectrometer has three main components: a collimator, prism table and a telescope. In Experiment 1 of this course, you have learnt the functions of each of these components and how to set it up for doing experiments using a prism. For completeness we reiterate some of the major steps. First you have to level the spectrometer using screws given at its base. Thereafter, we level the prism table using spirit level and then align the collimator and the telescope for parallel rays.

The adjustments required to set-up a spectrometer before working with it are: (i) the axis of the spectrometer is to be made vertical so that it coincides with the vertical axis of rotation of the prism table; (ii) the axes of the collimator and the telescope should be made horizontal so that they are perpendicular to the axis of the prism table/spectrometer; (iii) the refracting faces of the prism should be vertical so that it is parallel to the axis of rotation of the telescope; and (iv) the collimator and the telescope should be adjusted for parallel rays. The procedure to achieve these adjustments is given in Sec. 1.3.1 of Experiment 1. You should follow the procedure explained there and set-up the spectrometer for making measurements.

Once you have set-up the spectrometer, you are ready to measure the angle of the prism and the angle of minimum deviation for violet, yellow and red colours.

7.3.2 Angle of Prism using Sodium Light

1. Set up the spectrometer as explained in the previous Section.
2. Determine the least count of the vernier scales of the spectrometer as described in Sec. 1.4.1 of Experiment 1.
3. Switch on the sodium vapour lamp. (The sodium vapour lamp could be switched on in the beginning of the experiment as it takes some time to radiate yellow light fully.)
4. Place the prism on the prism table so that its refracting edge *AB* and *AC* faces the collimator as shown in Fig. 7.3. In this position, the parallel beam of light coming from the collimator falls on both the refractive surfaces of the prism. See that the slit is visible from both the faces with naked eye.

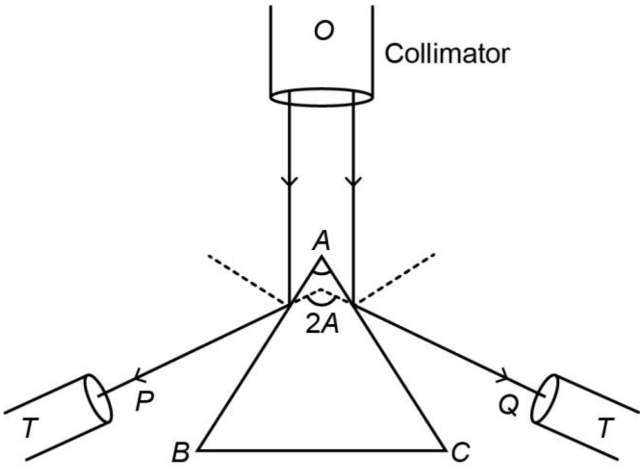


Fig. 7.3: **Measurement of the angle of prism.**

5. Move the telescope to a position, say *P*, so as to receive light after reflection from face *AB* and you can see the image of the slit.

6. Adjust the vertical cross-wire of the eye piece so that it coincides with the image of the slit.

7. Note the reading of main scale as well as vernier scale on both the vernier windows V_1 and V_2 in the Observation Table 7.2.

8. Now, rotate the telescope and bring it to a position, say *Q* so as to receive light after reflection from face *AC.* Make sure that you can see clear image of the slit once again.

9. Note the reading of main scale and vernier scale on both the vernier windows V_1 and V_2 in the Observation Table 7.2.

10. Take two independent set of readings for telescope positions at *P* and *Q* each.

11. The angle between these two positions is equal to 2*A*. You can easily calculate the value of the angle of the prism, *A*.

Observation Table 7.2: Angle of the prism (*A*)

Least Count of the main scale (M.S.) of the spectrometer = ………

Least Count of the vernier scales (V.S.) of the spectrometer = ……

No. of Observations	**Vernier**	**Telescope at position *P***			**Telescope at position *Q***			**Difference of totals** (2*A*)(°)	**Value of** (*A*)(°)
		MSR	**VSR**	**Total 1 = [MSR + (VSR× LC)]**	**MSR**	**VSR**	**Total 2 = [MSR + (VSR× LC)]**		
1	Vernier 1								
	Vernier 2								
2	Vernier 1								
	Vernier 2								

Mean value of the angle of the prism, *A* =..........

7.3.3 Angle of Minimum Deviation for Lights of Red, Yellow and Violet Colours

As you have learnt in Sec. 7.1, the refractive index of a transparent material depends on the wavelength of light. You also know that we need to determine the refractive indices of the given prism for lights of three different colours to determine the dispersive power of the prism. For this, you have to measure the angles of minimum deviation for each of these three colours.

To get lights of violet, yellow and red colours, you will use mercury vapour lamp for this part of the experiment. Follow the following steps for determining the angle of minimum deviation. We first explain it with reference to the light of red colour:

1. Place the prism on the prism table with one of its faces *AB* facing the collimator and the centre of the prism coinciding with the centre of the table as shown in Fig. 7.4.

2. Switch on the mercury vapour lamp.

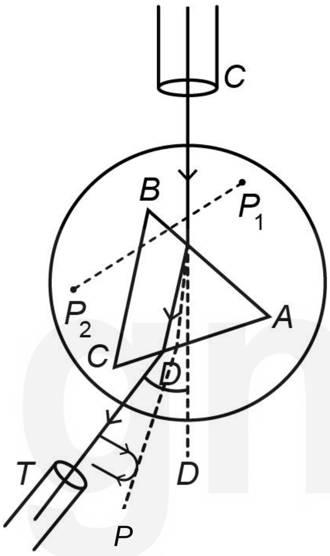


Fig. 7.4: **Measurement of the angle of minimum deviation.**

3. Look, with unaided eye, through the other face *AC* of the prism. You will observe a series of brightly coloured images of the slit formed due to refracted rays (refer to Fig. 7.5 which shows the spectrum of mercury).

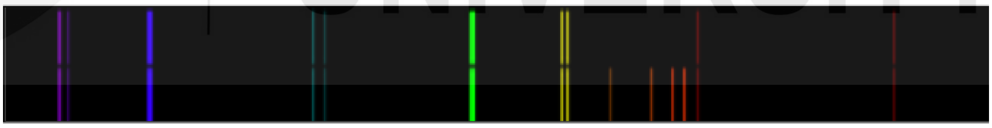


Fig. 7.5: **Spectrum of mercury vapour light.**

4. Now, focus on any prominent colour, say the red colour, and rotate the prism table slowly in such a direction that the image seen by the eye moves as close as possible to the direct ray from the collimator (shown by *D* in Fig. 7.4). While doing this, you will note that at a particular stage, the image will begin to move away from the direct ray. In other words, the image will just start to move in backward direction. This position of the prism corresponds to the position of minimum deviation for the red colour.

5. Bring the telescope to this position (position *P* in Fig. 7.4). Adjust the vertical cross-wire of the eye piece with the slit image.

6. Rotate the prism table slightly with the help of tangent screw so that the image moves in the direction of decreasing deviation.

7. Rotate the telescope using the tangent screw to align its cross-wire with the slit image. This is the precise position of the prism for minimum deviation.

8. Note down both the vernier readings in the Observation Table 7.3.

9. The difference between the mean readings for the minimum deviated ray and the direct ray (position *D* in Fig. 7.4) gives the angle of minimum deviation δ_m of the prism for the red colour.

Observation Table 7.3: Angle of minimum deviation (δ_m)

Least Count (LC) of vernier scale = ………

Line	Vernier	Telescope at position *P* (for minimum deviation ray)			Telescope at position *D* (for direct ray)			Difference, (*a*~*b*) $(\delta_m)(°)$	Mean $(\delta_m)(°)$
		MSR	VSR	Total (*a*) = [MSR +(VSR × LC)]	MSR	VSR	Total (*b*) = [MSR +(VSR × LC)]		
Red	Vernier 1								
	Vernier 2								
Yellow	Vernier 1								
	Vernier 2								
Violet	Vernier 1								
	Vernier 2								

10. Now move the telescope gently and set on the yellow line. Adjust the vertical cross-wire on the yellow line with the help of the tangent screw. Take readings of both the verniers and note down in Observation Table 7.3.

11. Repeat the same process for violet line and note down the readings in the Observation Table 7.3.

12. Now, remove the prism from the prism table. Align the telescope with the direct ray from the collimator so as to see the red colour image of the slit. Using the tangent screw of the telescope, adjust the vertical cross-wire of the eye piece with the fine slit image.

13. Note the readings of both the verniers for this position of the telescope and record in the Observation Table 7.3. This is the **direct ray reading**. (This one set of readings of both the verniers (Vernier 1and Vernier 2) can be used for all the lines/colours.)

7.4 CALCULATIONS AND RESULTS

On the basis of the measurement of the angle of the prism and the angles of minimum deviation for the lights of different colours, you can easily calculate the refractive index of the prism for each of these colours using Eq. (7.1). And, using the values of these refractive indices, you can determine the dispersive power of the material of the prism using Eq. (7.8).

Refractive index for red colour, $\mu_{red} =$ ………..

Refractive index for red colour, $\mu_{yellow} =$ ……..

Refractive index for red colour, $\mu_{violet} =$ ………

Dispersive power of the material of the prism, ω = …………

Go to the Academic Counsellor to know the material of your prism. Compare the experimentally determined value of the dispersive power of the material of the prism with the theoretical value.

EXPERIMENT 8

RESOLVING POWER OF A PRISM

Structure

8.1 INTRODUCTION

As you know, spectrometer is an optical equipment used for spectral analysis of polychromatic light such as the white light (from the sun) and the light emitted by various elements. It is used to determine the wavelengths of colours emitted by these sources. For this purpose, we either use a prism or a grating. You now know that a prism as well as a grating has the property of separating different wavelengths in polychromatic incident light. The process of separation of light into constituent colours in a prism is refraction, a grating does so due to diffraction.

You will recall from the previous experiment that the phenomenon of separating/splitting different colours (wavelengths) of white light by a prism is called dispersion. (Note that the colour of light is the visible manifestation of the light's wavelength). The (angular) separation between different wavelengths depends on the dispersive power of the prism which you learnt to determine in Experiment 7. Recall that the dispersive power of a prism depends on the refractive index of the prism for different wavelengths. It means that the dispersive power of the prism is one of its intrinsic properties.

For any optical measurement using a prism spectrometer, we view image of the source of light through a prism. So, it is necessary that two adjacent wavelengths are sufficiently separated from each other to be seen distinctly. You may now ask: Can we define a parameter which determines the separation between the two adjacent images or closely spaced objects is 'sufficient'?

The answer to this question is in the affirmative; such a parameter is called resolving power. In this experiment, you will learn to determine the resolving power of a prism using a spectrometer.

Expected Skills

After performing this experiment, you should be able to:

- ❖ set up spectrometer for taking measurements;
- ❖ observe different wavelengths emitted by a polychromatic source using a prism;
- ❖ observe the spreading of images of a linear source;
- ❖ measure small angular separation using a spectrometer; and
- ❖ calculate the resolving power of a prism.

You will require the following apparatus for this experiment.

Apparatus Required

Spectrometer, prism, spirit level, reading lens (magnifying glass), mercury vapour lamp, an adjustable micrometer slit.

8.2 DIFFRACTION AND RESOLUTION

You may be aware that human eye cannot see two objects or two points on an object distinct from each other if the angle subtended by them on the eye is less than one sixtieth of a degree, i.e., one minute. It means that for an object at a distance of about 25 cm from the eye, two objects/ points on the same object closer than 1 mm will not be seen as distinct (Fig. 8.1) because the angle subtended at the eye is less than 1 min. That is, the images of the two points formed in the eye cannot be construed as different/separate. In such a situation, we say that the eye is not able to resolve them.

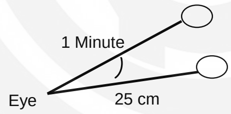


Fig. 8.1: **Two points on an object subtending angle on the eye.**


(a) (b) (c)

Fig. 8.2: **Images (diffraction patterns) of a) a single point source; b) two point sources separated by a distance; c) two point sources placed very close to each other.**

Do you know as to why human eye is unable to resolve two nearby points or objects? This happens because of diffraction of light. You have studied diffraction of light in Block 3 of the course entitled Waves and Optics (BPHCT-137). When light passes through a narrow slit, it spreads out to some extent into the region of its geometrical shadow with the result that the edges of the shadow are not sharp. Similarly, when light passes through a circular aperture such as that of a camera, telescope, microscope or human eye, we observe a spot with fuzzy edges due to diffraction of light by the circular aperture (Fig. 8.2a).

Thus, if we view two point sources of light placed close together, their images will overlap somewhat, as shown in Fig. 8.2b. But, we can still say that these images correspond to two different point sources. However, if the two point sources are very close to each other, their images will overlap to a very large extent and we cannot distinguish between them (Fig. 8.2c). It implies that diffraction of light puts a limit on how close two point sources can be for them to be seen as two distinct points. That is, resolution of two points is limited or constrained by diffraction and due to diffraction of light, we cannot see two objects as distinct from each other unless they are located at some minimum distance from each other. This minimum separation defines the limit of resolution of the optical instrument.

On the basis of the above discussion, we can say that the **resolving power** of an optical instrument such as human eye, telescope or microscope is its ability to produce distinctly separate images of two nearby objects. The **limit of resolution** of the human eye is about 1 minute. (This is the angle subtended by two points separated by about 0.15 mm at a distance of 25 cm from the eye.) That is, two objects must subtend an angle more than 1 minute on the eye to be seen as two distinct entities (Fig. 8.1). Mathematically, the resolving power of an optical instrument is the reciprocal of the minimum angular separation at which two point objects can just be seen as two distinct entities.

Rayleigh's Criterion

Rayleigh suggested a criterion for resolution of two closely located objects in terms of the intensity distribution associated with the diffraction patterns produced by them, as follows:

Two sources are said to be just resolved by an optical instrument if the principal maximum of the diffraction pattern due to one falls on the first minimum of the diffraction pattern of the other and *vice-versa*.

From Unit 10 of BPHCT-137, you may recall that the intensity distribution curve corresponding to the diffraction pattern produced by a single source consists of a central maximum and a few faint maxima and minima, as shown in Fig. 8.3.

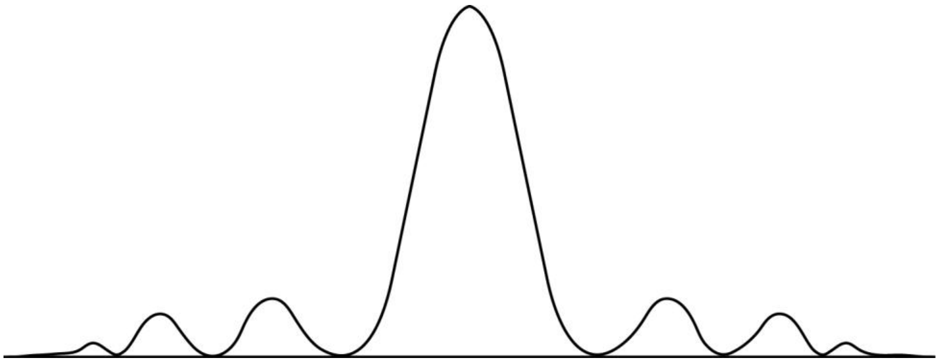


Fig. 8.3: **Intensity distribution curve of diffraction pattern due to a single source.**

If two sources (objects) are kept close to each other then the intensity of diffraction pattern of the sources are as shown in Fig. 8.4. Note that the resultant intensity of the diffraction pattern is shown by the dashed line. Also note from Fig. 8.4 that the maximum of one distribution curve falls exactly on the first minimum of the other and *vice-versa*. According to the Rayleigh's criterion, when this condition is met, the two objects are said to be just resolved; that is, they are seen as two distinct objects. And when the intensity maxima of the two patterns are closer than this separation, the two sources cannot be resolved. That is, the sources would appear to have merged and appear as one source.

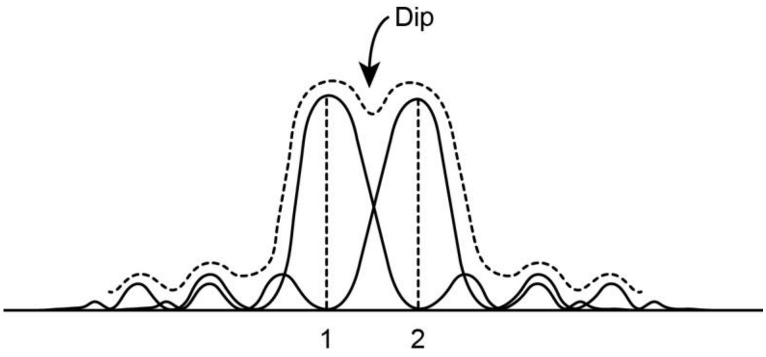


Fig. 8.4: **Intensity distribution curves of diffraction patterns due to two sources 1 and 2.**

You may now ask: What do we mean by the resolving power of a prism? Let us learn about it now.

8.2.1 Resolving Power of a Prism

Recall that a prism has a unique property/ability to split polychromatic light incident on it in separate wavelengths. This dispersive property of prism arises due to the fact that the refractive index of a prism depends on the wavelength of light which causes lights of different wavelengths to be refracted at different angles by a prism. This property of prism is used in spectral analysis of electromagnetic waves emitted by a source in the visible range. However, the image of a source of light of a given wavelength spreads out as it passes through the prism. For two close wavelengths to be seen as distinct images/lines after passing through a prism, we expect that there would be some (minimum) separation between them. So, the resolving power of a prism is a measure of its ability to form distinct images of two spectral lines of very close wavelengths.

When light from a mercury vapour lamp passes through a slit source and is incident on a prism, we observe distinct coloured lines through the eye piece of the spectrometer. (These are essentially images of the slit corresponding to each wavelength.) If the wavelengths of two just resolved spectral lines are λ and $\lambda + d\lambda$, then $\lambda/d\lambda$ defines the measure of the resolving power of the prism.

To determine the resolving power of a prism experimentally, we need an expression in terms of experimentally measurable quantities. Refer to Fig. 8.5, which shows the section *ABC* of a prism. Suppose that a monochromatic light of wavelength λ from the collimator is incident on the face *AB* of the prism, which has been placed in the position of minimum deviation. Let us now assume that light covers the whole of face *AB* of the prism. Let *BM* be the incident wavefront and CN_1 the emergent wavefront which gives rise to image I_1 in the focal plane of the lens *L*. If μ is refractive index of the material of the prism for the light of wavelength λ and t is the thickness of the base of the prism, then by noting that the **optical path** between BM and CN_1 must be the same, we can write

$$MA + AN_1 = \mu\,(BC)$$

$$= \mu t \qquad (8.1)$$

Now, we assume that light of wavelength $\lambda + d\lambda$ is incident on the face AB of the prism and it produces an emergent wavefront CN_2 that gives rise to image I_2. If $d\mu$ denotes the change (decrease) in the refractive index of the prism due to $d\lambda$ increase in the wavelength (in accordance with the Cauchy's relation), then we can write

$$MA + AN_2 = (\mu - d\mu)t \qquad (8.2)$$

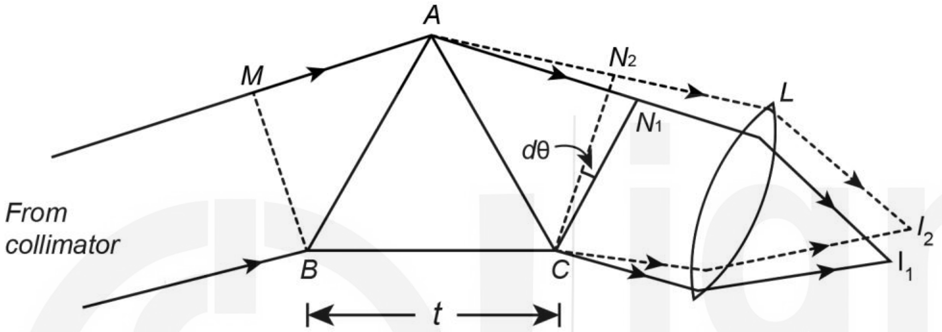


Fig. 8.5: A beam of light from a source incident on the refracting face of a prism giving rise to the image / of the source

On subtracting Eq. (8.2) from Eq. (8.1), we get

$$AN_1 - AN_2 = t\,d\mu$$

or $$N_1 N_2 = t\,d\mu \qquad (8.3)$$

If 'a' denotes the width of the emergent wave front CN_1 and $d\theta$ is the angle between CN_1 and CN_2, then

$$a\,d\theta = N_1 N_2 = t\,d\mu \qquad (8.4)$$

Also, the limiting condition for resolution of telescope of the spectrometer is given by

$$d\theta = \frac{\lambda}{a}$$

where a is the aperture of the objective lens of the telescope (assuming that the wavefront completely covers the aperture of the objective lens).

Thus, on substituting the above expression for $d\theta$ in Eq. (8.4), we get

$$\frac{\lambda}{a} = t\,\frac{d\mu}{a} \qquad (8.5)$$

On dividing both sides of Eq. (8.5) by $d\lambda$, we get the expression for resolving power of a prism:

$$\frac{\lambda}{d\lambda} = t\,\frac{d\mu}{d\lambda} \qquad (8.6)$$

Note that $d\mu / d\lambda$ signifies the change in refractive index of the prism with the change in wavelength. This is also called the **chromatic dispersion** of the material of the prism. Do you know that it is related to dispersive power of a prism? To show this, we refer to Experiment 7 where you learnt to obtain mathematical expression for dispersive power of a prism [Eq. (7.8)]:

$$\omega = \frac{(\mu_v - \mu_r)}{(\mu_y - 1)} = \frac{d\mu}{d\lambda} \tag{8.7}$$

It shows that resolving power of a prism and its dispersive power are related as

$$\text{R. P.} = t.\omega \tag{8.8}$$

However, you are advised to use Eq. (8.6) as the working formula in this experiment:

$$\text{R.P.} = t\,\frac{d\mu}{d\lambda} \tag{8.9}$$

where t is the thickness of the base of the prism and $d\mu / d\lambda$ is the rate of change of refractive index with the wavelength.

We can obtain the value of $d\mu / d\lambda$ using Cauchy's empirical relation:

$$\mu = A + \frac{B}{\lambda^2} \tag{8.10}$$

where A and B are Cauchy's constants.

On differentiating both sides of Eq. (8.10) w.r.t. λ, we get

$$\frac{d\mu}{d\lambda} = -\frac{2B}{\lambda^3} \tag{8.11}$$

Thus, Eq. (8.9) can be written as

$$\text{R.P.} = t\,\frac{d\mu}{d\lambda} = -\frac{2Bt}{\lambda^3} \tag{8.12}$$

The – ve sign in Eq. (8.12) indicates that μ decreases as λ increases.

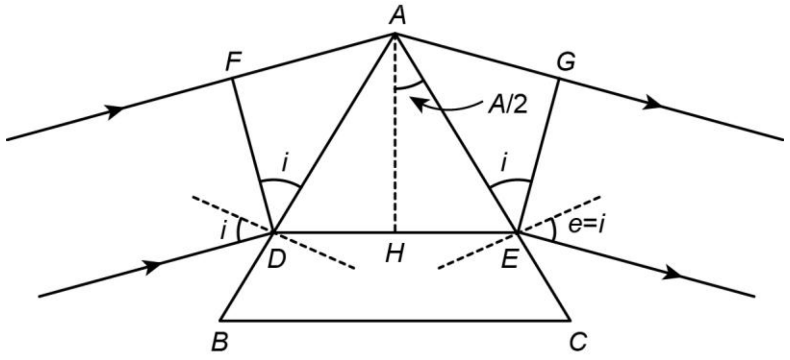


Fig. 8.6: **Light incident on the refracting face of a prism. The effective thickness of the prism for the incident beam is** *DE.*

Generally, the whole thickness t of the base of the prism is not used in the experimental set up. So, you should determine the **effective thickness** (actual value of t) of the prism so that Eq. (8.12) can be used for calculating resolving power. To do so, note from Fig. 8.6 that, for triangle $AEG,$ we can write

$$AE\cos i = GE = a$$

since *EG* is normal on *AG* and *a* is the separation between the two rays. Similarly from triangle *AFD*, we can write

$$FD = GE = a$$

Since, *AH* is Normal on *DE*, we can write the expression for

$$\text{Effective thickness, } t = DE = 2DH = 2HE$$

$$= 2AE\sin(A/2)$$

$$= 2\frac{a}{\cos i}\sin(A/2) \qquad (8.13)$$

When the prism is set in the minimum deviation position, we have

$$A + \delta_m = i + i = 2i$$

or $$i = \frac{A + \delta_m}{2} \qquad (8.14)$$

So, on substituting for i from Eq. (8.14) in Eq. (8.13), we get

$$t = \frac{2a\sin(A/2)}{\cos\left(\dfrac{A+\delta_m}{2}\right)} \qquad (8.15)$$

Recall that in addition to thickness *t*, we also need to determine Cauchy's constant *B* to obtain the resolving power of the prism. Cauchy's constant *B* can be determined, for the purpose of this experiment, by using the expression for the refractive index for just two wavelengths (ideally, we need to have values of the refractive index for more than three wavelengths for determination of Cauchy's constants; you have learnt to do that in Experiment 3 of this course):

$$\mu_1 = A + \frac{B}{\lambda_1^2} \quad \text{and} \quad \mu_2 = A + \frac{B}{\lambda_2^2}$$

where μ_1 and μ_2 are the refractive indices corresponding to wavelengths λ_1 and λ_2 , respectively. On combining the expressions for μ_1 and μ_2, we can write

$$\mu_1 - \mu_2 = B\left(\frac{1}{\lambda_1^2} - \frac{1}{\lambda_2^2}\right) \text{ so that } B = \frac{(\mu_1 - \mu_2)(\lambda_1^2.\lambda_2^2)}{(\lambda_2^2 - \lambda_1^2)} \qquad (8.16)$$

On using Eqs. (8.15) and (8.16) in Eq. (8.12), you can easily determine the resolving power of the prism.

8.3 PROCEDURE

In this experiment, you need to measure (i) the angle of the prism, (ii) angle of minimum deviation, (iii) aperture of the slit source, and (iv) effective thickness of the prism. These measurements are to be used to calculate refractive index of the prism and Cauchy's constant, *B* to determine the resolving power of the prism. We now describe the procedure to make these measurements and do the required calculations. But, before taking any measurement using the spectrometer, you must adjust the spectrometer using the steps given in Sec. 1.3.1. That is, you have to level its base as well as that of the prism table, align the collimator and the telescope for parallel rays and adjust the eye piece. Once the spectrometer has been adjusted, you are ready to make measurements.

8.3.1 Angle of Prism

You have learnt to measure the angle of the prism in Experiments 1 and 7. Follow the steps given in Sec. 1.3.2 of Experiment 1(or in Sec. 7.3.1of Experiment 7) to determine the angle of the given prism. You should use any one wavelength of mercury vapour lamp as source for this measurement. Complete the table given below for recording your readings in Observation Table 8.1 for the angle of the prism. (You need to make your table.)

Observation Table 8.1: Angle of the prism

Least count of the main scale (M.S.) of the spectrometer = ………

Least count (LC) of the vernier scales of the spectrometer = ……

Sl. No.	**Vernier**	**1st Position of Telescope (*X*)**			**2nd Position of Telescope (*Y*)**			**Difference (*Y*– *X*) = 2*A***	**Angle of Prism (*A*)**
		MSR	**VSR**	**Total**	**MSR**	**VSR**	**Total**		
1	V_1								
	V_2								
2	V_1								
	V_2								

Mean value of the angle, *A* of the prism =...........

You should get a value of about 60 degree. In case your result shows large deviation, you should repeat the steps and calculate the angle of prism again.

8.3.2 Angle of Minimum Deviation

As can be seen from Eq. (8.16), you need to calculate refractive index of the prism for two different wavelengths λ_1 and λ_2 to determine the Cauchy's constant *B*. To this end, you need to determine the angle of minimum deviation of the prism for these two wavelengths. You have learnt to do this measurement in Experiment 7. Use the mercury vapour lamp as source and follow the steps given in Sec. 7.3.2 of Experiment 7 to measure the angle of minimum deviation for two wavelengths λ_1 and λ_2 of yellow colour which are very close to each other by taking readings of both the verniers V_1 and V_2 of the spectrometer. Complete the observation table (Observation Table 8.2) given below and record your readings.

The wavelengths of the two nearby yellow lines of the mercury vapour lamp are:

$$\lambda_1 = 5769.9\ \text{Å} \quad \text{and} \quad \lambda_2 = 5790.7\ \text{Å}$$

Observation Table 8.2: Angle of minimum deviation for wavelengths λ_1 and λ_2

Sl. No.	Line/ Wave-length	Vernier	Minimum Deviation Ray (*X*)			Direct ray (*Y*)			Difference (*Y*– *X*) = (δ_m)	Mean (δ_m)
			MSR	VSR	Total	MSR	VSR	Total		
1	λ_1	V_1								
		V_2								
2	λ_2	V_1								
		V_2								

8.3.3 Aperture of the Slit

To measure the aperture, *a* of the slit, follow the steps given below:

1. While keeping the prism in the position of minimum deviation, attach an adjustable micrometer slit in front of the telescope objective. Keep the slit aperture sufficiently wide at this stage.
2. Now slowly decrease the width of the micrometer slit with the help of attached micrometer screw till the two yellow lines are just seen as separate (resolved). Record the micrometer reading in Observation Table 8.3.
3. Further turn the screw till the micrometer slit just gets closed without applying extra force. Note down the reading again. The difference of these two readings gives the width of the slit (i.e. aperture) *a*.
4. Now open the slit slowly by turning the screw till light appears again and the two yellow lines are just resolved. Note the reading. The difference gives *a*.
5. Repeat steps 2, 3 and 4 one more time while closing and opening the slit.
6. Calculate the mean value of *a*.

Observation Table 8.3: Slit width (aperture)

No. of Obser-vation	Micrometer Reading						Mean '*a*'
	While closing			While opening			
	Lines just resolved	Slit closed	Difference '*a*'	Lines just resolved	Slit closed	Difference '*a*'	
1.							
2.							

[**Note:** In case the adjustable slit with micrometer scale is not available in the laboratory, you can do the experiment with an ordinary adjustable slit and measure its width *a* in this position when it was just resolving the two yellow lines of the spectrum by using a travelling microscope also. If you measure the slit width (aperture) using a travelling microscope, use the following observation table (Observation Table 8.4).]

Observation Table 8.4: Slit width (aperture) using Travelling Microscope

Least count of travelling microscope =

No. of observation	**Cross wire focussed on one edge of slit** X_1	**Cross wire focussed on other edge of slit** X_2	**Slit width '*a*'** $(X_1 \sim X_2)$	**Mean '*a*'**
1.				
2.				

8.4 CALCULATIONS AND RESULTS

The value of slit width (aperture) (Observation Table 8.3 (or 8.4)) is:

a = …………

The value of the angle of the prism (Observation Table 8.1) is:

A = …………

Using the values of the angles of minimum deviation δ_{m1} and δ_{m2} corresponding to wavelength λ_1 and λ_2, calculate μ_1 and μ_2 using the formula:

$$\mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin(A/2)}$$

Calculate the value of Cauchy's constant *B* using the values of λ_1, λ_2, μ_1 and μ_2 in Eq. (8.16):

B = ...

For calculating the effective thickness (*t*) of the prism, use the mean of δ_{m1} and δ_{m2} for δ_m in Eq. (8.15):

t = ...

Substituting the values of *B, t* and mean of λ_1 and λ_2 as λ in Eq. (8.12), calculate the value of the resolving power (R.P.) of the prism.

Result: The resolving power of the given prism = ...

EXPERIMENT 9

DIFFRACTION FROM A WIRE

Structure

9.1 INTRODUCTION

From our everyday experience, we know that we can hear people talking in an adjoining room whose door is open. This is due to bending of sound waves around the corners of the door. Similarly, if you closely examine shadows cast by objects, you will observe that the edges of shadows are not sharp. This is because the light has bent slightly due to diffraction at the edges of the object and entered the shadow region. And if you look at a distant street lamp at night and squint, you will observe that light appears to streak out. This is because light has bent around the corners of your eyelids. The bending of light around corners is known as diffraction. Diffraction is exhibited by all waves; mechanical waves such as sound and water waves as well as electromagnetic waves such as light or radio waves.

The objects we come across in everyday life are generally about 10^5 times bigger than the wavelength of light. In such a situation, though diffraction of light does occur but it is not prominent and light appears to follow a rectilinear path. When the size of the objects/obstacle, either transparent or opaque becomes comparable to the wavelength of light, diffraction effects are prominently observed. However, it is important to note that diffraction of light by even macroscopic objects can be observed under suitable conditions. One of the objectives of this experiment is to observe diffraction of light by a macroscopic object in the form of a thin wire.

You have learnt in Block 3 of Waves and Optics course (BPHCT-137) that systematic explanation of diffraction phenomenon was given by Fresnel on the basis of Huygens principle. You have also learnt that diffraction is classified into two categories, namely Fresnel diffraction and Fraunhofer diffraction. When the distance between the source (of light) and the obstacle as also the distance between the obstacle and the observation screen are finite, we obtain what is called Fresnel diffraction. And, when these distances are infinite, we observe Fraunhofer diffraction. But the distances in a physics laboratory are finite. Then, you may like to know: How do we ensure infinite distances between the source, obstacle and the observation screen? It is done by using lens and keeping the source and the observation screen at the focus of convex lens. The theoretical analysis of diffraction of light leads to a relation between the wavelength of the light used, size of the obstacle, angular position of the diffraction fringes and distance between the obstacle and the observation screen. Therefore, by obtaining diffraction patterns for different types of obstacles and taking measurements of required quantities, we can determine the wavelength of the light used. In this experiment, you will obtain Fraunhofer diffraction pattern of a thin wire using a laser source and determine the wavelength of the laser light.

Expected Skills

After performing this experiment, you should be able to:

- handle a laser source;
- measure thickness of a wire using a travelling microscope;
- obtain Fraunhofer diffraction pattern of a thin wire;
- measure the distance of minima from the principal maximum in the diffraction pattern; and
- determine the wavelength of the given laser light.

Before proceeding to perform the experiment, you should know the apparatus listed below.

Apparatus Required

Laser source, safety goggles, screen, ruled-paper/graph paper, thin -wire, measuring tape, and travelling microscope.

9.2 DIFFRACTION OF LIGHT

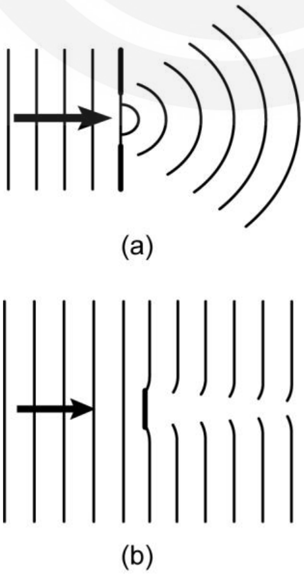


Fig. 9.1: **Cross-sectional view of diffraction from a) an aperture/slit, b) a wire.**

When light is incident on a very small (of the order of the wavelength of light) obstacle such as a slit or a wire, it spreads/bends around the edges (Fig. 9.1). Note that the plane wavefronts (representing the light beam) incident on an obstacle (slit/wire) become curved due to bending around the edges while passing across the obstacle. The diffraction effect is a general characteristic of waves and it occurs whenever a portion of the wavefront is obstructed.

From Block 3 of the Waves and Optics (BPHCT-137) course, you may recall that Fresnel diffraction is observed when either the source and the obstacle or the obstacle and the observation screen are separated by a finite distance, i.e.

are close to each other. On the other hand, Fraunhofer diffraction is observed when source and the observation screen are effectively at infinite distances from the obstacle. You may ask: What do we mean by ‘close to each other’ in case of Fresnel diffraction and ‘effectively at infinite distance’ in case of Fraunhofer diffraction? To get an idea of these distances, refer to Fig. 9.2 which depicts diffraction of light from a distant point source *S* by a slit of width *b* on a screen placed at distance *r* from the slit.

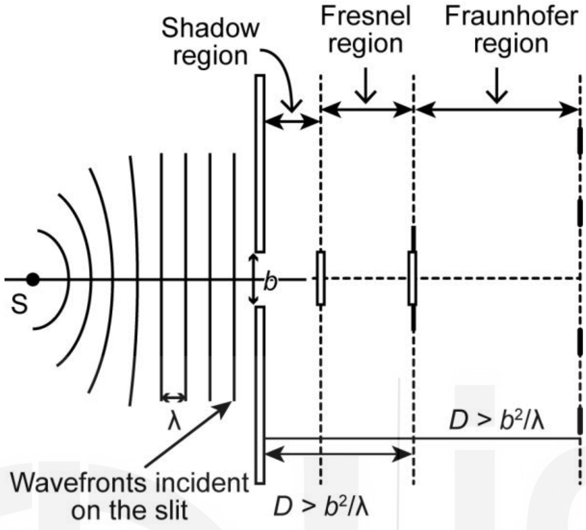


Fig. 9.2: **Plane wavefronts from a distant light source *S* diffracted by a slit of width *b*.**

We are said to be in the Fresnel region when the condition $D \le b^2/\lambda$ is satisfied and Fraunhofer diffraction region when the condition $D \ge b^2/\lambda$ is satisfied as shown in Fig. 9.2. You should note from the conditions specifying the Fresnel and Fraunhofer regions depend on the size of the aperture/obstacle and the wavelength of light for a given separation, *D* between the obstacle and the screen.

The theoretical understanding of diffraction given by Fresnel is based on Huygens principle of wave propagation. You learnt about this in Unit 4 of BPHCT-137. According to this principle, every point on a wavefront acts as a point source of spherical secondary waves (called wavelets) of the same frequency and speed as the original primary wave. The wavefront at some later instant is the envelope of these secondary wavelets at that instant. You would recall that Huygens could successfully explain the phenomena of reflection and refraction on the basis of this principle, but it failed to explain as to what happens with the backward travelling secondary spherical wavelets. To overcome the limitations of Huygens Principle, Fresnel introduced the idea of interference of secondary wavelets: Every point on a primary wavefront can be thought of as source of secondary wavelets whose envelop and interference forms the wavefront at some later instant. The modified version of Huygens principle, called **Huygens-Fresnel principle,** provided a satisfactory explanation of the phenomena of diffraction. You have studied the detailed theoretical explanation of Fresnel and Fraunhofer diffractions from a variety of obstacles in Block 3 of BPHCT-137.

Let us now learn about the diffraction pattern for a thin wire which is the task at hand for you in this experiment.

9.2.1 Diffraction from a Wire

In this experiment, you will learn to obtain Fraunhofer diffraction pattern of a thin wire using a laser source and determine the wavelength of the laser light. But for the brightness of the central spot, Fraunhofer diffraction pattern produced by a thin wire is very similar in nature to that produced by a slit (Fig. 9.3).

Fig. 9.3: **Intensity distribution in the diffraction patterns of a single slit and a wire.**

The similarity between the diffraction patterns of a slit and a wire is explained on the basis of **Babinet's Principle**. According to this principle, if we consider two complementary diffracting objects such as a slit and an obstacle of same size and shape such as a wire, the diffraction pattern will be same when either of the complementary objects is used by itself. [You will be able to verify this when you do the next experiment (Experiment 10) of this course.] Further, Fig. 9.3 schematically depicts the intensity distribution corresponding to the diffraction patterns produced by a slit and a thin wire. From Fig. 9.3, we note that the salient features of the diffraction patterns of a wire and a slit are:

1. The diffraction pattern consists of a horizontal streak of light along a line perpendicular to the wire/slit.
2. The horizontal pattern consists of a series of bright spots and the spot at the centre is the brightest. The central spot is called **principal maximum.**
3. On either side of the central spot, there are a few more bright spots of diminishing brightness situated symmetrically. These are called **secondary maxima.**

The ray diagram showing diffraction due to a slit and a wire are schematically depicted in Fig. 9.4. Note that, unlike for the slit (case *B*), the light diffracting around the edges of the wire (case *A*) are directed towards the central spot where they interfere constructively. In fact, this is true for the entire wavefront above and below the wire: light diffracting from upper portion and the lower portion interfere constructively at the central spot on the observation screen.

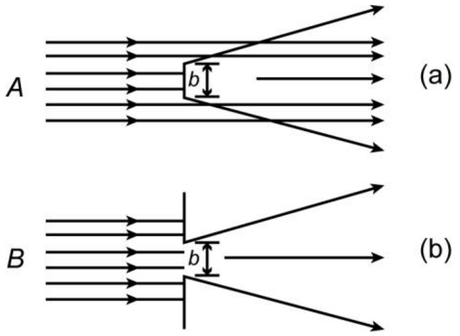


Fig. 9.4: **Incident and diffracted rays from a) a wire, b) a slit.**

As a result, the central spot of the diffraction pattern of the wire is brighter than central spot of the diffraction pattern of a slit.

As discussed above, the nature of the observed diffraction patterns of a wire and a slit of comparable dimensions is similar except for the brightness of the central spot. We now explain the theoretical basis of these diffraction patterns by considering the diffraction from a slit. We assume that a plane wavefront of light from a distant source is incident on a diffracting slit *AB* whose width is *b* (Fig. 9.5). The diffraction pattern is observed on a screen located at a distance *D* from the slit. You may now ask: What will be the intensity of diffracted light at any given point on the observation screen? To determine the intensity at any point in the diffraction pattern, we use Huygens-Fresnel principle. We divide the slit *AB* into a number of points $A, A_1, A_2,\ A_3 \ldots B$ and assume that each of these points acts like a source of secondary wavelets. According to Huygens-Fresnel principle, the intensity at any point in the diffraction pattern will depend on the nature of interference of these secondary wavelets at that point. If the secondary wavelets interfere constructively, the point will have high intensity and will appear bright but if the secondary wavelets interfere destructively, the intensity will be low or zero and the point will appear dark.

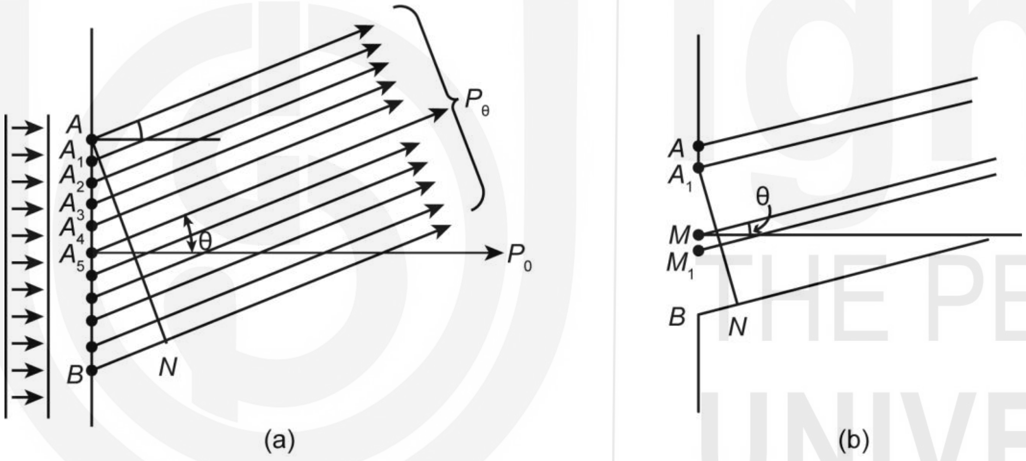


Fig. 9.5: **Cross-sectional view of the geometry for single slit diffraction.**

Now, let us consider a point P_θ on the screen which makes an angle θ with the axis (Fig. 9.5a). In order to sum up the contributions of different wavelets emanating from the slit at point P_θ, we need to know their amplitudes and phases. The amplitudes of the disturbances from $A, A_1,\ A_2 \ldots$ will be very nearly equal because the distance of the point on the screen from the slit *D* is very large compared to the width of the slit (that is, *D*>>*b*). To determine how the phases of the disturbances sum up at any point on the screen, the slit is divided into *n* equal parts and the path difference between each pair is calculated. From Unit 9 of the BPHCT-137 course, you may recall the detailed mathematical derivation for the intensity at a point in the Fraunhofer diffraction pattern of a single slit. Here we quote the result only:

$$I_\theta = I_0 \left(\frac{\sin\beta}{\beta} \right)^2 \qquad (9.1)$$

where, I_θ is the intensity at a point in the diffraction pattern located at angle θ from the axis, $I_0 \left(= A^2\right)$ is the intensity at the central point ($\theta = 0$), $A = na_0$ is the sum of amplitudes due to n equal parts of the slit wavefront with a_0 being the amplitude of each part, and

$$\beta = \pi \frac{b \sin\theta}{\lambda} \qquad (9.2)$$

where λ is the wavelength of light and b is the slit width. Eq. (9.1) gives the intensity distribution (intensity for different values of θ spanning the entire diffraction pattern) in the diffraction pattern and explains the experimentally observed pattern. From Eq. (9.1), you may note that the intensity is maximum for $\theta = 0$ [because (sin β/β) = 1] and specifies the central point of the pattern. This point is called principal maximum of the pattern. The intensity gradually decreases on either side of the principal maximum and becomes zero when $\beta = \pm\pi$ because $\sin(\pm\pi) = 0$. So, we can write the condition for minima in the diffraction pattern as

$$\beta = \pm\pi, \pm 2\pi, \pm 3\pi ... = m\pi \qquad (9.3)$$

where $m = \pm 1, \pm 2, \pm 3 ...$ represents the order of diffraction. Note that the value $m = 0$ has been excluded as it corresponds to the principal maximum ($\beta = 0$). Thus, from Eqs. (9.2) and (9.3), we can write the condition for minima as

$$b \sin\theta = m\lambda, \qquad m = \pm 1, \pm 2, \pm 3 ... \qquad (9.4)$$

You will get a clear idea of the single slit pattern on the basis of the following qualitative arguments and using Eq. (9.4). To do so, refer to Fig. 9.5b. Note that the path difference between the wavelets emanating from the extreme points *A* and *B* of the slit and reaching point P_θ is $BN = b\sin\theta$. You know that when *BN* is an integral multiple of λ, the resultant intensity at point P_θ will be zero. From Eq. (9.4), we know that, for $m = 1$, $b \sin\theta = \lambda$.

Now, let us divide the slit *AB* into two equal parts *AM* and *MB* as shown in Fig. 9.5b. Consider the wavelets starting from two point sources *A* and *M*. The path difference between them is

$$AM \sin\theta = (b/2)\sin\theta = (\lambda/2)$$

Thus, the phase difference between the waves from points *A* and *M* will be π and superposition of these two waves will result in zero intensity at point P_θ. Similarly, for point A_1 just below point *A*, there will be a point M_1 just below point *M* such that the path difference between the wavelets generated at these points will be $\lambda/2$ .On superposition, this pair also leads to zero intensity at point P_θ. We can similarly pair off all the points in the upper half (*AM*) of the slit with corresponding points in the lower half (*MB*) such that the effect of waves from the upper half of the slit will be cancelled by the waves from the lower half. So, the resultant intensity at point P_θ will be zero and it will be minima in the diffraction pattern. Thus, we may conclude that we will get minimum intensity at a point in the diffraction pattern for which the path difference between the rays from the extremes of the slit is equal to λ.

To check the validity of the above conclusion, let us consider the case $m = 2$ so that the path difference between the waves from extremes *A* and *B* of the slit is [Eq. (9.4)]: $b \sin\theta = 2\lambda$. We can imagine that the slit is now divided into four equal parts and by similar pairing, you can argue that the first and the second quarters have a path difference of $\lambda/2$ and cancel the effects of each other. By the same argument,, the third and fourth quarters would cancel out each other. That is, the resultant intensity at point P_θ will be zero. Similarly, for $m = 3$, we can divide the slit into six equal parts and can show that, in each of the three pairs, the two halves will cancel out effects of one another and we will again get zero intensity at P_θ. Thus, when the path difference between the rays diffracted from the extremes in a particular direction (determined by θ) is an integral multiple of λ, the resultant diffracted intensity in that direction will be zero.

Now, for the purpose of this experiment and required measurements, refer to Fig. 9.6, which is a simplified version of Fig. 9.5.

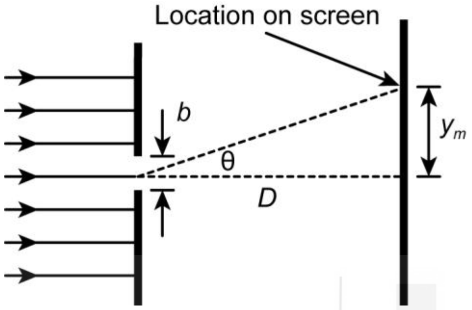


Fig. 9.6: **Cross-sectional view of the geometry for single slit diffraction.**

We know that light is diffracted by a slit of width *b* and the diffraction pattern is observed on a screen located at distance *D* from the slit. Let y_m is the distance of the m^{th} minima from the midpoint of the principal maximum. If θ is the angle of diffraction, the conditions for minima in the diffraction pattern are [Eq. (9.4)]:

$$b \sin\theta = m\lambda$$

From Fig. 9.6, you may write

$$\sin\theta = y_m \Big/ \sqrt{D^2 + y_m^{\,2}}$$

If the screen is placed far away (~ 1.0 to 1.5 m) from the slit, we have the condition $D >> y_m$. So, we can write

$$\sin\theta = y_m / D$$

With this value of $\sin\theta$, the condition for minima takes the form

$$b(y_m / D) = m\lambda$$

or,
$$\lambda = (b y_m / mD) \qquad (9.5)$$

Eq. (9.5) shows that we can determine the wavelength of light once you know the slit width *b* and the distance y_m of the *m*th minima from the midpoint of the principal maximum.

You may now ask: Can we use Eq. (9.5) for a wire (of comparable thickness) instead of the slit? The answer is in affirmative; you can use Eq. (9.5) even if the diffraction pattern has been obtained using a wire as an obstacle. The distance of minima from the centre of the principal maximum remains the same for the diffraction pattern caused by a wire of same thickness as in case of the slit according to Bebinet's principle. The only difference is that the centre of the diffraction pattern of the wire would look brighter because the percentage of the laser beam that is not diffracted by the wire adds to the intensity of the centre of the pattern.

9.3 PROCEDURE

To determine the wavelength of laser light using Fraunhofer diffraction pattern of a wire, you need to (i) measure the thickness of the wire, (ii) obtain a sharp diffraction pattern of the wire using the laser light whose wavelength is to be determined, and (iii) measure the distance between the principal maximum and minima in the diffraction pattern. The procedures for these activities are given below.

9.3.1 Measurement of Thickness of Wire

1. Firstly, determine the least count (LC) of the vernier scale of the travelling microscope and note it down in Observation Table 9.1.
2. Place the wire mounted on the frame vertically near the objective of the microscope. Keep the wire at a distance of about 10 cm from the microscope objective.
3. Move the microscope horizontally and locate the image of the wire.
4. With the help of the focusing knob, obtain a sharp image of the wire.
5. With the help of the fine adjustment screw for horizontal movement of the microscope, align the cross wire of the eye piece with the left edge of the wire. Fix the position of the microscope with the help of the screw. Note down the main scale and vernier scale readings in the Observation Table 9.1.
6. Move the microscope slowly towards other edge of the wire and keep looking through the eye piece. Align the cross wire of the eye piece with the right edge of the wire. Fix the position of the microscope. As before, note down the main scale and vernier scale readings in the Observation Table 9.1.
7. Take 2 to 3 readings at different points along the length of the wire by repeating steps 3 to 6 and note down the readings in the Observation Table 9.1.

Observation Table 9.1: Thickness of the wire

Least Count of the Travelling Microscope: …….. … cm

No. of Obs.	**Reading of Microscope**						**Thickness** ***b*** **(X~*Y*)**	**Average Thickness of Wire (*b*)**
	Reading of left edge (*X*)			**Reading of right edge (*Y*)**				
	MSR	**VSR**	**Total (*X*)**	**MSR**	**VSR**	**Total (*Y*)**		
1								
2								
3								

9.3.2 Obtaining Diffraction Pattern

1. Arrange the laser, wire and the observation screen along a line as depicted in Fig. 9.7.

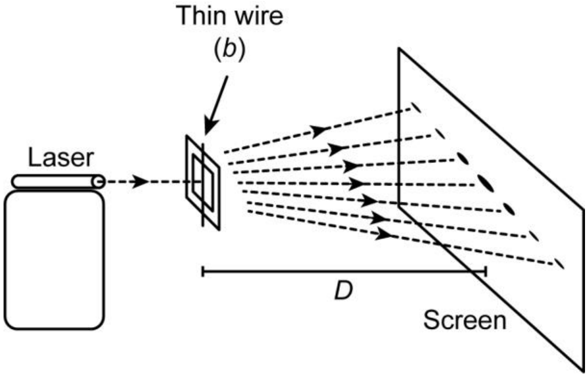


Fig. 9.7: **Experimental set up for diffraction from a wire.**

2. Ensure that the wire is taut and the distance between the wire and the observation screen (which may be a wall) is around 1.5 to 2.0 m. Mark the position of the wire stand and move it aside.
3. On the screen, attach a ruled- paper with the help of adhesive tape or clips such that the ruled scale is horizontal. (You may also use graph paper in place of ruled-paper.)

   [Caution: The laser beam can damage your eyes if you look into it either directly or by reflection from some shiny objects. Therefore, you must be extremely careful and never let your eyes be in the direct or reflected line of the laser. Always wear laser goggles. Also, you should not turn the laser off and on too frequently.**]**
4. Turn the laser on. With no wire in between the laser and the screen, you should observe a sharp spot on the screen. Adjust the height of the laser and the screen so that the laser spot is observed directly on the ruled lines in the middle of the paper/graph paper.
5. Now, bring the wire (vertically) in the path of the laser beam at the place marked in step 2. You will observe a horizontal streak of bright spots (diffraction pattern) as shown in Fig. 9.1. Adjust the distance between the wire and the screen to make the diffraction pattern sharp.

9.3.3 Measurement of Distance of Minima from Principal Maximum

1. To measure the distance, y_m between the central maximum and m^{th} minima, mark the fringe pattern with pencil on edges of bright spots on both left and right side of the central maximum as shown in Fig. 9.8. Record the readings of the edges in Observation Table 9.2.

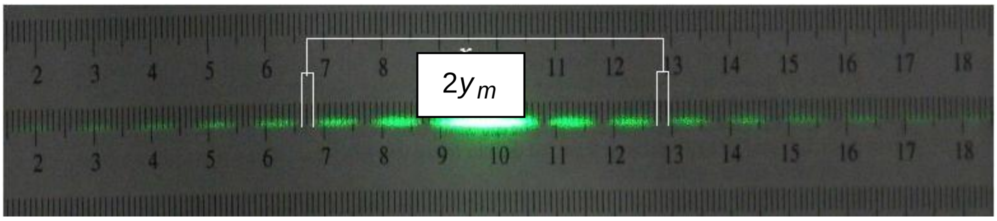


Fig. 9.8: **Measurement of distance between minima on the two sides of the central maximum in the diffraction pattern.**

2. Calculate the midpoints of minima for each value of m (= 1, 2, 3, etc.) and subtract one from other to determine y_m $[= (y_m^l \sim y_m^r)/2]$. (You may not be able to get sharp bright and dark spots for m greater than 3. For the

present experiment, taking measurements up to m = 3 should be good enough.)

3. Measure the distance between the wire and the screen using a measuring tape.

Distance between wire and the screen, D = ……….. cm.

Observation Table 9.2: Distance of minima from principal maximum

Order of minima (m)	Minima Position on the left of principal maximum			Minima Position on the right of principal maximum			Difference (X~Y) = 2y_m	Average y_m
	MSR	VSR	Total (X)	MSR	VSR	Total (Y)		
1								
2								
3								

9.4 CALCULATIONS AND RESULTS

To calculate the value of the wavelength of the laser light, you need to substitute the values of b (Observation Table 9.1), D and y_m (Observation Table 9.2) in Eq. (9.5).For m =1 (first order minima), Eq. (9.5) takes the form:

$$\lambda = (by_1/D) = \text{.........}\,\text{nm}$$

Similarly, you can calculate the value of λ using data for second and higher order minima and substituting them in Eq. (9.5). Take the average of these values of λ.

Result: The wavelength of laser light, $\lambda =$..........nm

EXPERIMENT 10

STUDY OF SINGLE SLIT DIFFRACTION OF A LASER USING PHOTO SENSOR

Structure

10.1 INTRODUCTION

In the last experiment you learnt about the diffraction pattern generated by a thin wire. As you know, diffraction is a property of light in which it deviates from a straight path as it passes an obstacle or through a very fine slit having a width comparable to the wavelength of light being used. You are aware that there are two classes of diffraction, namely, Fresnel and Fraunhofer diffraction and in this experiment we will focus on the latter. We will investigate the nature of the diffraction pattern which essentially consists of maxima and minima of varying intensities. A photo sensor will be used to study the intensity changes in the diffraction pattern. In this experiment, you will also understand the operation of a He-Ne laser.

Expected Skills

After performing this experiment, you should be able to:

- set up and obtain the diffraction pattern from a single slit;
- investigate the variation of intensity of a single slit diffraction pattern using laser; and
- explain the dependence of various parameters on which the intensity depends.

You will require the following apparatus to perform this experiment.

Apparatus Required

He-Ne laser, optical bench, single slits of different widths, laser protecting goggles, photo sensor, meter scale and screen.

10.2 INTENSITY DISTRIBUTION AND CONDITIONS FOR MAXIMA AND MINIMA

You are all familiar with the diffraction pattern produced when coherent light from a monochromatic source falls upon a vertical slit. You have studied this in detail in Unit 10 of the course BPHCT-137. The typical single slit diffraction pattern is shown in Fig.10.1, made up of consecutive maxima and minima. The central maximum is much larger than those on either side, and the intensity decreases rapidly on either side of the centre. The maxima and minima are produced by the constructive and destructive interference of the light reaching the screen from different parts of the slit. The resultant intensity is therefore different at different places on the screen. What factors does the intensity depend on?

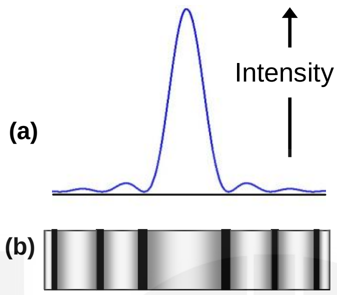


Fig. 10.1: **a) Intensity distribution in a single slit Fraunhofer diffraction pattern; b) observed pattern on a screen.**

Consider that a plane wavefront (like that from a laser source) is incident on a diffracting slit as shown in Fig. 10.2. The diffraction pattern is formed on a screen place at a distance *L* from the slit. *OO*' is a straight line perpendicular to the screen from the centre of the slit *O*.

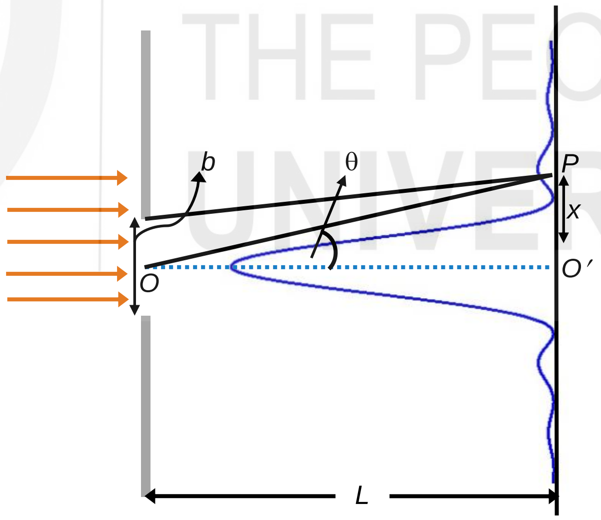


Fig. 10.2: **Ray diagram of light propagation through a single slit.**

P is a point situated at a distance x from the point *O*′ on the screen. The line *OP* joins the point *P* to the centre of the slit. The angle between *OO*′ and *OP* is θ. The intensity of the diffraction pattern at *P* is given by the following relation (Eq. 10.8 of Unit 10, BPHCT-137):

$$I_\theta = I_0\left[\frac{\sin\left(\frac{\pi b\sin\theta}{\lambda}\right)}{\left(\frac{\pi b\sin\theta}{\lambda}\right)}\right]^2 = I_0\left[\frac{\sin\beta}{\beta}\right]^2 \qquad (10.1)$$

where $\beta = \frac{\pi b \sin\theta}{\lambda}$. Here *b* is the width of the slit and λ is the wavelength of light. I_0 is the intensity of the central maxima. The intensity is maximum for $\theta = 0$ $(I = I_0)$ and it falls off on either side of the central maximum.

The condition for a maximum in the diffraction pattern is

$$\beta = \left(m + \frac{1}{2}\right)\frac{\pi}{2} \rightarrow b\sin\theta \cong \left(m + \frac{1}{2}\right)\lambda, \text{ where } m = 0, \pm 1, \pm 2, \pm 3, ... \quad (10.2)$$

For a minimum in the diffraction pattern the, condition is

$$\beta = m\pi \rightarrow b\sin\theta \cong m\lambda, \text{ where } m = 0, \pm 1, \pm 2, \pm 3, ... \quad (10.3)$$

So the width of the central maximum is

$$b\sin\theta = \lambda \quad (10.4)$$

For small values of the angle θ,

$$\sin\theta \cong \tan\theta = \frac{x}{L} \quad (10.5)$$

So the slit width *b* can be evaluated from the width of the central maxima using the equation:

$$b = \frac{\lambda L}{x} \quad (10.6)$$

10.3 DESCRIPTION OF THE APPARATUS

10.3.1 Description of the Laser

You have learnt in Unit 12 of the course of Optics (BPHCT-137) that a Helium-Neon (He-Ne) laser is a four-level laser in which Helium and Neon gases are mixed in the ratio 10:1. The gas mixture is placed in a long discharge tube fitted with plane mirrors, one being highly reflective while the other is partially transparent, maintained at a pressure of approximately 1 mm of mercury. It produces a beam of light with high coherence and directionality. The most prominent wavelength in the visible region, occurring at 632.8 nm, is used for performing the experiment. Energy is transferred from the excited He atoms to the Ne atoms on colliding, resulting into lasing action.

[**Caution:** You must ensure that the laser beam never points directly into anyone's eyes as it can cause severe and permanent damage. Switch off the laser when it is no longer in use.]

10.3.2 Description of the Photo Sensor

The photo sensor is a device sensing electromagnetic radiation, especially, light. It converts light received as an optical signal into an electrical signal that can be measured as voltage or current depending on the device. A *p-n* junction made of suitable combination of materials is the commonly used photo sensor, it absorbs photons through an illumination window with an anti-reflective coating and generates equivalent electron-hole pairs in the depletion region, which can be collected and analyzed using appropriate electronic circuit.

[**Caution:** The laser and the photo sensor must be placed as far apart as possible.]

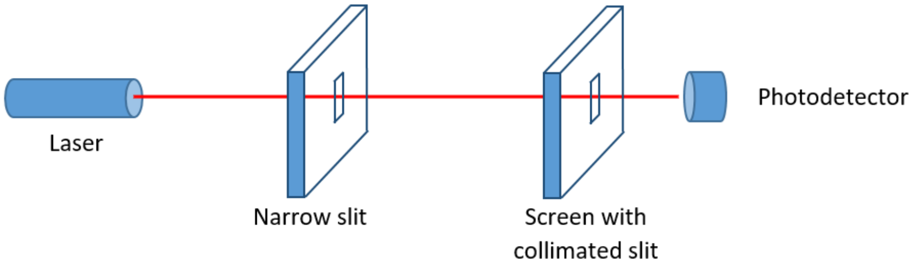


Fig. 10.3: **Set-up for observing the single slit diffraction pattern as viewed from the side.**

10.4 EXPERIMENTAL PROCEDURE

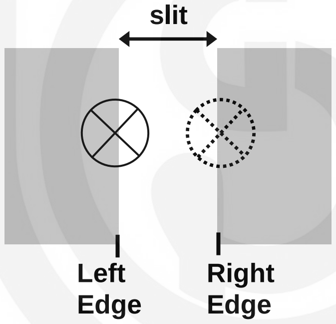


Fig. 10.4: **Cross-wires of the travelling microscope focussed on the left and right edge of the slit.**

1. Arrange the source, slit and screen/ photo sensor as shown in Fig. 10.3. Optimise the position of the slit for a clear diffraction pattern to be observed on a screen (for a particular slit width). A proper alignment must be done for the laser light to fall on the slit and the screen.
2. You may adjust the distance between the slit and the screen in order to achieve a sharp and clear diffraction pattern.
3. Adjust the position of the photo sensor to measure the intensity in terms of current at the central maxima. The intensity is different at different positions as shown in Fig. 10.2. Note down the position of the photo sensor with the help of the micrometer fitted on it and the corresponding current/voltage from the detector in Observation Table 10.1.
4. Now move the photo sensor to another position and take readings of the position and corresponding current/voltage at this position. Continue to take the reading on the same side of the central maxima.
5. Repeat Step 4 for different positions on the other side of the central maxima.
6. To measure the slit width you will use a travelling microscope. First of all measure its least count. Then focus one edge of the slit on the cross-wire, as shown in Fig. 10.4 and take the reading. Then focus the microscope on the other edge of the slit and take the reading. The slit width is the difference between the readings. Take an average after sets of readings. (Observation Table 10.2)
7. Measure the distance between the slit and the screen (*L*) with the help of a meter scale thrice and take the average.

Observation Table 10.1: Variation of photo sensor response with respect to position

Least count of the circular scale of the micrometer = ………….. mm

Position	MSR (mm)	VSR (mm)	Total (mm)	Current/ Voltage (A / V)
Position of the Photo Sensor (Right to the Central Maxima)				
1.				
2.				
3.				
4.				
5.				
Position of the Photo Sensor (Left to the Central Maxima)				
6.				
7.				
8.				
9.				
10.				

Observation Table 10.2: Measurement of the slit-width using a travelling microscope

Least count of the microscope = …………………………………..

S. No	Cross-wire set on Left edge of the Slit			Cross-wire set on Right edge of the Slit			Width of the Slit (*a*–*b*) (mm)	Mean Slit Width
	MSR	VSR	Total (*a*) (mm)	MSR	VSR	Total (*b*) (mm)		
1.								
2.								
3.								

Average value of the slit width, *b* =……… mm

10.5 CALCULATIONS AND RESULTS

1. Plot a graph of the photo sensor reading (current/voltage) as a function of distance. (Take distance on *x*-axis and current/voltage on *y*-axis.)
2. Mark the position of the central maximum and calculate the slit width by taking the distance *x* from the centre maxima and dividing by the *L* using Eq. (10.6). Match your results with the slit width calculated from Observation Table 10.2.