10

POLARIZATION

10.1 INTRODUCTION

Experiments on interference and diffraction have shown that light is a form of wave motion. These effects do not tell us about the type of wave motion *i.e.*, whether the light waves are longitudinal or transverse, or whether the vibrations are linear, circular or torsional. The phenomenon of polarization has helped to establish beyond doubt that light waves are transverse waves.

10.2 POLARIZATION OF TRANSVERSE WAVES

Let a rope *AB* be passed through two parallel slits S_1 and S_2. The rope is attached to a fixed point at *B* [Fig. 10.1(*a*)]. Hold the end *A* and

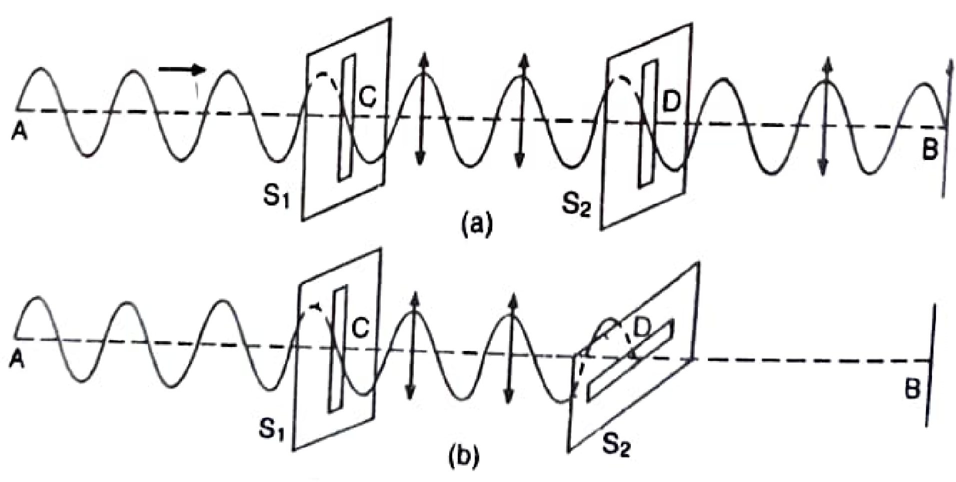

Fig. 10.1

move the rope up and down perpendicular to *AB*. A wave emerges along *CD* and it is due to transverse vibrations parallel to the slit S_1. The slit S_2 allows the wave to pass through it when it is parallel to S_1. It is observed that the slit S_2 does not allow the wave to pass through it when it is at right angles to the slit S_1 [Fig. 10.1(*b*)].

If the end A is moved in a circular manner, the rope will show circular motion up to the slit S_1. Beyond S_1, it will show only linear vibrations parallel to the slit S_1, because the slit S_1 will stop the other components. If S_1 and S_2 are at right angles to each other the rope will not show any vibration beyond S_2.

If longitudinal waves are set up by moving the rope forward and backward along the string, the waves will pass through S_1 and S_2 irrespective of their position.

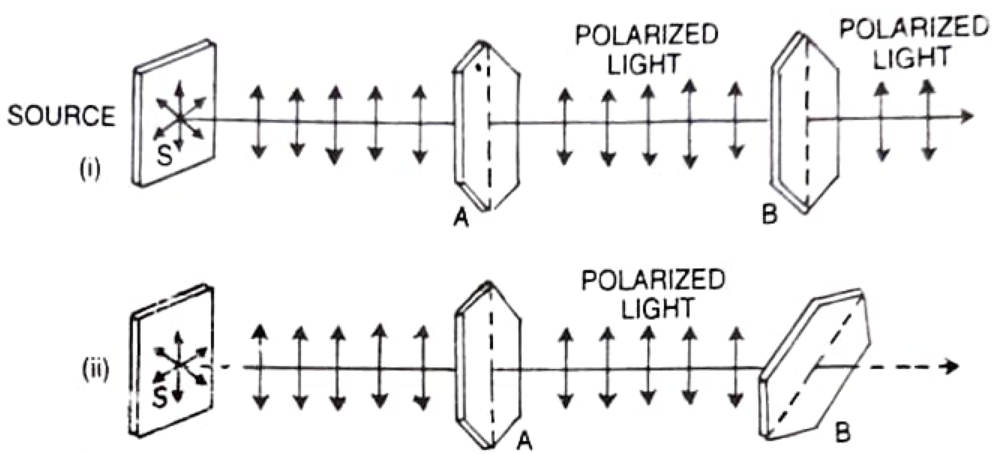

Fig. 10.2

A similar phenomenon has been observed in light when it passes through a tourmaline crystal.

Let light from a source S fall on a tourmaline crystal A which is cut parallel to its axis (Fig. 10.2). The crystal A will act as the slit S_1. The light is slightly coloured due to the natural colour of the crystal. On rotating the crystal A, no remarkable change is noticed. Now place the crystal B parallel to A.

(1) Rotate both the crystals together so that their axes are always parallel. No change is observed in the light coming out of B [Fig. 10.2 (*i*)].

(2) Keep the crystal A fixed and rotate the crystal B. The light transmitted through B becomes dimmer and dimmer. When B *is at right angles to* A, no light emerges out of B [Fig. 10.2 (*ii*)].

If the crystal B is further rotated, the intensity of light coming out of it gradually increases and is maximum again when the two crystals are parallel.

This experiment shows conclusively that light is not propagated as longitudinal or compressional waves. If we consider the propagation of light as a longitudinal wave motion then no extinction of light should occur when the crystal B is rotated.

It is clear that after passing through the crystal A, the light waves vibrate only in one direction. Therefore light coming out of the crystal A is said to be **polarized** because it has acquired the property of **one sidedness** with regard to the direction of the rays.

This experiment proves that light waves are transverse waves, otherwise light coming out of B could never be extinguished by simply rotating the crystal B.

10.3 PLANE OF POLARIZATION

When ordinary light is passed through a tourmaline crystal, the light is polarized and vibrations are confined to only one direction perpendicular to the direction of propagation of light. This is plane polarized light and

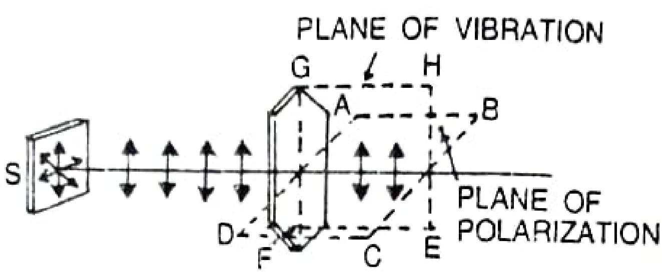

Fig. 10.3

it has acquired the property of one sidedness. The plane of polarization is that plane in which no vibrations occur. The plane *ABCD* in Fig. 10.3 is the plane of polarization. The vibrations occur at right angles to the plane of polarization and the plane in which vibrations occur is known as plane of vibration. The plane *EFGH* in Fig. 10.3 is the plane of vibration.

Ordinary light from a source has very large number of wavelengths. Moreover, the vibrations may be linear, circular or elliptical. From our idea of wave motion, circular or elliptical vibrations consist of two linear vibrations at right angles to each other and having a phase difference of $\frac{\pi}{2}$.

Therefore any vibration can be resolved into two component vibrations at right angles to each other. As light waves are transverse waves the vibrations can be resolved into two planes xx' and yy'

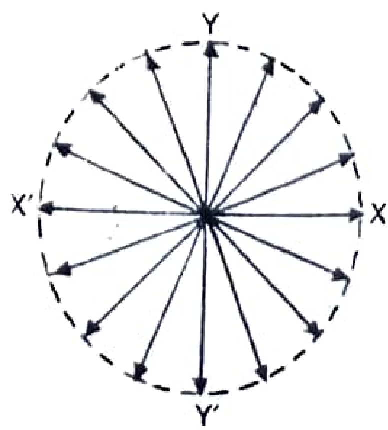

Fig. 10.4

at right angles to each other and also perpendicular to the direction of propagation of light (Fig. 10.4).

In Fig. 10.5(*i*), the vibrations of the particles are represented parallel (arrow heads) and perpendicular to the plane of the paper (dots).

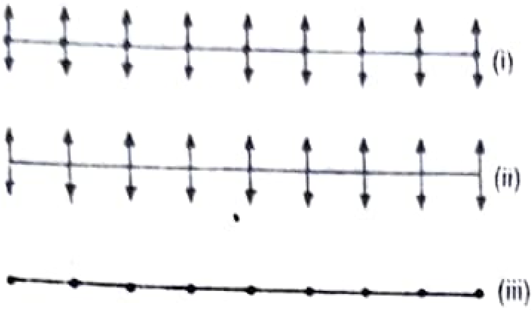

Fig. 10.5

In Fig. (10.3) (*ii*) the vibrations are shown only parallel to the plane of the paper. In Fig. (10.5) (*iii*) the vibrations are represented only perpendicular to the plane of the paper.

10.4 POLARIZATION BY REFLECTION

Polarization of light by reflection from the surface of glass was discovered by Malus in 1808. He found that polarized light is obtained when ordinary light is reflected by a plane sheet of glass. Consider the light incident along the path *AB* on the glass surface (Fig. 10.6). Light is

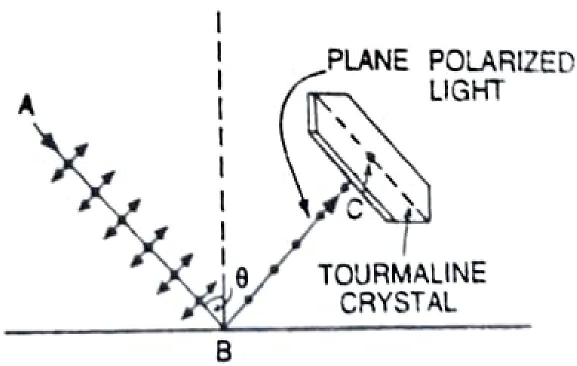

Fig. 10.6

reflected along *BC*. In the path of *BC*, place a tourmaline crystal and rotate it slowly. It will be observed that light is completely extinguished only at one particular angle of incidence. This angle of incidence is equal to 57.5° for a glass surface and is known as the polarizing angle. Similarly polarized light by reflection can be produced from water surface also.

The production of polarized light by glass is explained as follows. The vibrations of the incident light can be resolved into components parallel to the glass surface and perpendicular to the glass surface. Light due to the components parallel to the glass surface is reflected whereas light due to the components perpendicular to the glass surface is transmitted.

Thus, the light reflected by glass is plane polarized and can be detected by a tourmaline crystal.

The polarized light has been analysed by using another mirror by Biot.

10.5 BIOTS POLARISCOPE

It consists of two glass plates M_1 and M_2 (Fig. 10.7). The glass plates are painted black on their back surfaces so as to avoid any reflection and this also helps in absorbing refracted light. A beam of unpolarized light AB is incident at an angle of about 57.5° on the first glass surface at B and is reflected along BC (Fig. 10.8). This light is again reflected at 57.5° by the second glass plate M_2 placed parallel to the first. The glass plate M_1 is known as the polarizer and M_2 as the analyser.

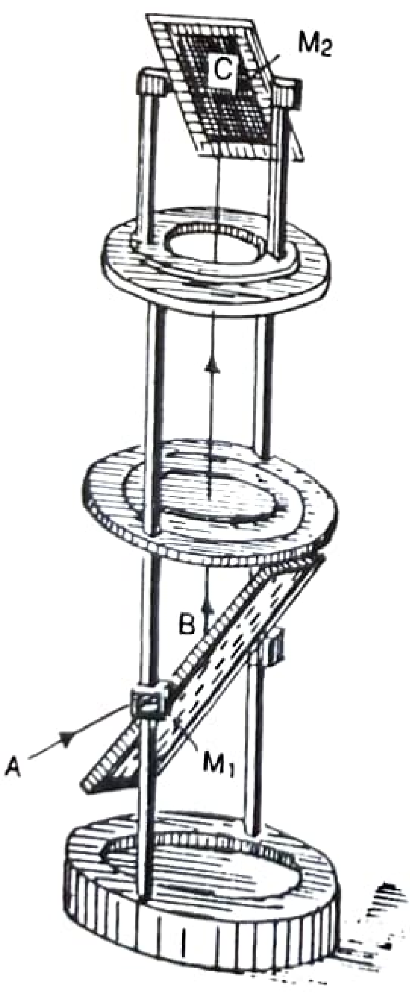

Fig. 10.7

When the upper plate M_2 is rotated about BC, the intensity of the reflected beam along CD decreases and becomes zero for 90° rotation of M_2. Remember, the rotation of the plate M_2 about BC, keeps the angle of incidence constant and it does not change with the rotation of M_2. Thus we find that light travelling along BC is plane polarized.

When the mirror M_2 is rotated further it is found that the intensity of CD becomes maximum at 180°, minimum at 270° and again maximum at 360°.

The above

the displacements are confined to a certain direction at right angles to the ray and we get polarized light by reflection.

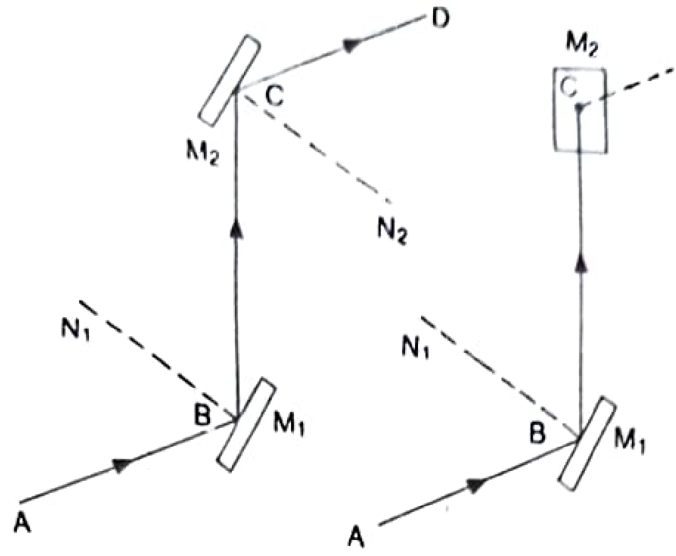

Fig. 10.8

10.6 BREWSTER'S LAW

In 1811, Brewster performed a number of experiments to study the polarization of light by reflection at the surfaces of different media.

He found that ordinary light is completely polarized in the plane of incidence when it gets reflected from a transparent medium at a particular angle known as the **angle of polarization.**

He was able to prove that the tangent of the angle of polarization is numerically equal to the refractive index of the medium. Moreover, the reflected and the refracted rays are perpendicular to each other.

Suppose, unpolarized light is incident at an angle equal to the polarizing angle on the glass surface. It is reflected along BC and refracted along BD (Fig. 10.9).

From Snell's law

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

From Brewster's law

$$\mu = \tan i = \frac{\sin i}{\cos i} \qquad ...(ii)$$

Comparing (*i*) and (*ii*)

$$\cos i = \sin r = \cos\left(\frac{\pi}{2} - r\right)$$

$$\therefore \quad i = \frac{\pi}{2} - r, \quad \text{or} \quad i + r = \frac{\pi}{2}$$

As $i + r = \frac{\pi}{2}$, $\angle CBD$ is also equal to $\frac{\pi}{2}$. Therefore, the reflected and the refracted rays are at right angles to each other.

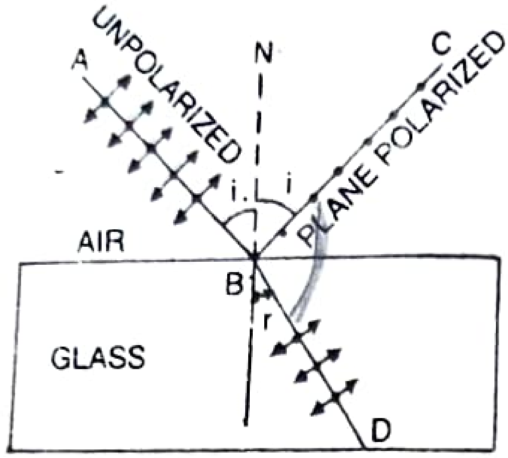

Fig. 10.9

From Brewster's law, it is clear that for crown glass of refractive index 1.52, the value of i is given by

$$i = \tan^{-1}(1.52) \quad \text{or} \quad i = 56.7^\circ$$

However, 57° is an approximate value for the polarizing angle for ordinary glass. For a refractive index of 1.7 the polarising angle is about 59.5° *i.e.*, the polarizing angle is not widely different for different glasses.

As the refractive index of a substance varies with the wavelength of the incident light, the polarizing angle will be different for light of different wavelengths. Therefore, polarization will be complete only for light of a particular wavelength at a time *i.e.*, for monochromatic light.

It is clear that the light vibrating in the plane of incidence is not reflected along BC [Fig. 10.9]. In the reflected beam the vibrations along BC cannot be observed, whereas vibrations at right angles to the plane of incidence can contribute for the resultant intensity. Thus, we get plane polarized light along BC. The refracted ray will have both the vibrations (*i*) in the plane of incidence and (*ii*) at right angles to the plane of incidence. But it is richer in vibrations in the plane of incidence. Hence it is partially plane-polarized.

10.7 BREWSTER WINDOW

One of the important applications of Brewster's law and Brewster's angle is in the design of a glass window that enables 100% transmission of light. Such a type of window is used in lasers and it is called a **Brewster window**.

When an ordinary beam of light is incident normally on a glass window, about 8% of light is lost by reflection on its two surfaces and about 92% intensity is transmitted. In the case of a gas laser filled with mirrors outside the windows, light travels through the window about a hundred times. In this way the intensity of the final beam is about 3×10^{-4} because $(0.92)^{100} \approx 3 \times 10^{-4}$. It means the transmitted beam has practically no intensity.

To overcome this difficulty, the window is tilted so that the light beam is incident at Brewster's angle. After about hundred transmissions, the final beam will be plane polarized.

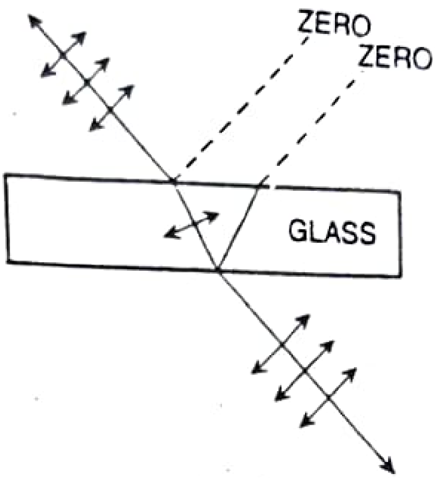

Fig. 10.10

The light component vibrating at right angles to the plane of incidence is reflected. After about 100 reflections at the Brewster window, the transmitted beam will have 50% of the intensity of the incident beam and it will be completely plane polarized. The net effect of this type of arrangement is that half the amount of light intensity has been discarded and the other half is completely retained. Brewster's windows are used in gas lasers.

10.8 POLARIZATION BY REFRACTION

It is found that at a single glass surface or any similar transparent medium, only a small fraction of the incident light is reflected.

For glass ($\mu = 1.5$) at the polarizing angle, 100% of the light vibrating parallel to the plane of incidence is transmitted whereas for the perpendicular vibrations only 85% is transmitted and 15% is reflected. Therefore, if we use a **pile of plates** and the beam of ordinary light is incident at the polarizing angle on the pile of plates, some of the vibrations perpendicular to the plane of incidence are reflected by the first plate and the rest are transmitted through it. When this beam of light is reflected by the second plate, again some of the vibrations perpendicular to the plane of incidence are reflected by it and the rest are transmitted. The process continues and when the beam has traversed about 15 or 20 plates, the transmitted light is completely free from the vibrations at right angles to the plane of incidence and is having vibrations only in the plane of incidence. Thus, we get plane-polarized light by refraction with the help of a pile of plates, the vibrations being in the plane of incidence as shown in Fig. 10.11.

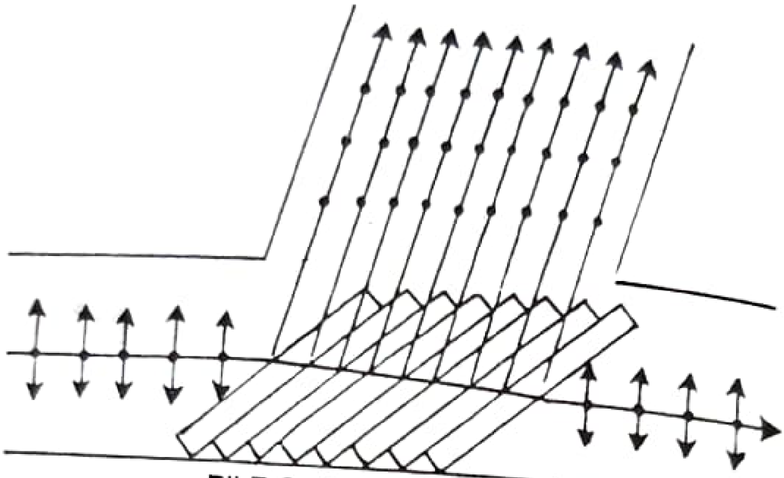

Fig. 10.11

The pile of plates consists of number of glass plates (microscope cover slips) and are supported in a tube of suitable size and are inclined at an angle of 32.5° to the axis of the tube. A beam of monochromatic light is allowed to fall on the pile of plates at the polarizing angle. The transmitted light is polarized perpendicular to the plane of incidence and can be examined by a similar pile of plates which works as an analyser.

Note. (*i*) If light is polarized perpendicular to the plane of incidence, it means vibrations are in the plane of incidence.

(*ii*) If light is polarized in the plane of incidence, it means vibrations are perpendicular to the plane of incidence.

10.9 MALUS LAW

When a beam of light, polarized by reflection at one plane surface is allowed to fall on the second plane surface at the polarizing angle the intensity of the twice reflected beam varies with the angle between the planes of the two surfaces. In the Biot's polariscope it was found that the intensity of the twice reflected beam is maximum when the two planes are parallel and zero when the two planes are at right angles to each other. The same is also true for the twice transmitted beam from the polarizer and analyser. The law of Malus states that the **intensity of the polarized light transmitted through the analyser varies as the square of the cosine of the angle between the plane of transmission of the analyser and the plane of the polarizer.** In the case of the Biot's polariscope this angle is between the two reflecting planes.

The proof of the law is based on the fact that any polarized vibration may be resolved into two rectangular components : (*i*) parallel to the plane of transmission of the analyser (*ii*) at right angles to it.

Let $OP = a$ be the amplitude of the vibrations transmitted or reflected by the polarizer and θ is the angle between the planes of the polarizer and the analyser (Fig. 10.12).

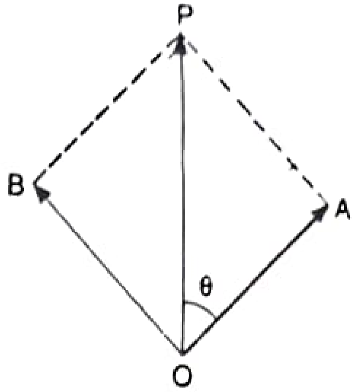

Fig. 10.12

Resolve OP into two components,

(*i*) $a \cos\theta$ along OA and

(*ii*) $a \sin\theta$ along OB.

Only the $a \cos\theta$ component is transmitted through the analyser.

∴ Intensity of the transmitted light through the analyser

$$E_1 = (a\cos\theta)^2 = a^2\cos^2\theta.$$

But $\quad E = a^2$

where E is the intensity of incident polarized light

∴ $\quad E_1 = E\cos^2\theta, \text{ and } \quad E_1 \propto \cos^2\theta$

When $\quad \theta = 0$ *i.e.*, the two planes are parallel

$E_1 = E$, because $\cos 0 = 1$

When $\quad \theta = \frac{\pi}{2}$ the two planes are at right angles to each other

∴ $$E_1 = E\left(\cos\frac{\pi}{2}\right)^2 = 0.$$

Example 10.1. *If the plane of vibration of the incident beam makes an angle of 30° with the optic axis, compare the intensities of extraordinary and ordinary light.*

Intensity of the extraordinary ray

$$I_E = A^2\cos^2\theta$$

Intensity of the ordinary ray

$$I_0 = A^2 \sin^2 \theta$$

$$\frac{I_E}{I_0} = \frac{A^2 \cos^2 \theta}{A^2 \sin^2 \theta} = \frac{\cos^2 \theta}{\sin^2 \theta}$$

Here $$\theta = 30^\circ$$

$\therefore$ $$E = \frac{I_E}{I_0} = 3$$

10.10 DOUBLE REFRACTION

Erasmus Bartholinus discovered, in 1669, that when a ray of light is refracted by a crystal of calcite it gives two refracted rays. This phenomenon is called **double refraction**. Calcite or Iceland spar is crystallised calcium carbonate (Ca CO_3) and was found in large quantities in Iceland as very large transparent crystals. Due to this reason calcite is also known as Iceland spar. It crystallises in many forms and can be reduced by cleavage or breakage into a rhombohedron, bounded by six parallelograms with angles equal to 102° and 78° (more accurately 101° 55′ and 78° 5′).

Optic Axis. At two opposite corners *A* and *H*, of the rhombohedron all the angles of the faces are obtuse [Fig. 10.13 (*a*)]. These corners *A* and *H* are known as the blunt corners of the crystal. A line drawn through *A* making equal angles with each of the