dichroism. This polaroid is colourless and transmits more light. The transmitted light is almost *completely polarised.*

(*iii*) Land and Rogers later discovered, that when the stretched poly-vinyl alcohol film is heated with a catalyst like hydro-chloric acid, it slightly darkens but exhibits strong dichroism. As the film does not contain any dyestuff, it is very stable and is not bleached by strong sunlight. It is called K-polaroid.

Uses : Polaroids have wide applications in every-day life. They are employed in automobile head lights, screens, sun glasses, windows of railway trains and aeroplanes' and in viewing stereoscopic motion pictures.

7.11. Nature of wave surfaces in uniaxial crystals.

When a ray is incident on the surface of an anisotropic medium, it is refracted into two rays—ordinary and extraordinary. Hence Huygens supposed that the secondary wave which is generated in an uniaxial crystal consists of two surfaces, one within the other. Laws of refraction are fully obeyed by ordinary ray, and hence the secondary wave-surface for this was assumed to be a sphere. As the extraordinary ray does not obey the laws of refraction, the wave-surface for this ray was assumed to be a spheroid (ellipsoid of revolution). No double refraction occurs when the incident ray travels along the optic axis of the crystal and hence it was supposed that the
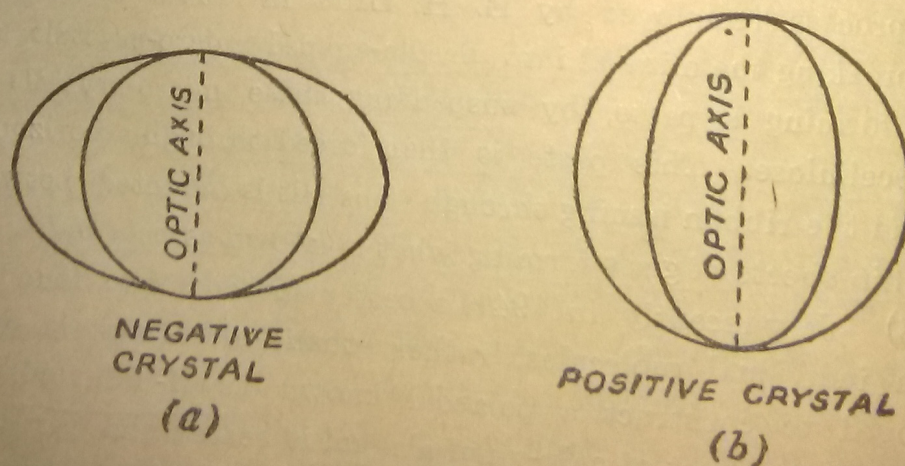

Fig. 7L

sphere and the spheroid touch each other in two points, which when joined gives the optic axis of the crystal.

In negative crystals like calcite, the extraordinary ray travels faster than the ordinary ray in a direction perpendicular to the axis and hence the sphere was considered with the spheroid [Fig. 7L(a)].

In positive crystals, like quartz, the ordinary ray travels faster than the extraordinary ray in a direction perpendicular to the axis and hence the spheroid was considered within the sphere [Fig. 7L(b)]. Though quartz is a uniaxial positive crystal, the sphere and spheroid do not quite touch at the optic axis. This fact gives rise to a phenomenon known as optical activity.

7.12. Huygens' construction of wave-surfaces in uniaxial crystal and their verifications.

Case I.—To show that laws of refraction are obeyed by O-ray but not by E-ray.

If a ray is incident on the surface of a crystal at a constant angle *i*, then due to the spherical nature of secondary waves for *O*-ray inside the crystal, the direction of the refracted *O*-ray should remain constant for all orientations of the axis of the crystal. But for the same incident ray, the secondary wave surface for *E*-ray would be spheroidal and hence the direction of the refracted *E*-ray would be different for different orientations of the axis of the crystal. This can be demonstrated by the following experiment.

Experiment.—Several prisms of the same size are cut from an iceland-spar so that the axes of different prisms are in different directions. These prisms are cemented together and put on the prism table of a spectrometer. When monochromatic parallel light from the collimator is made incident on this prism-combination we see that ordinary light from all prisms are in the same direction while the extraordinary light from different prisms are in different directions. This proves that ordinary light obeys, while the extraordinary light does not obey, the laws of refraction.

Case II.—Section of the wave surfaces by the plane of incidence which remain perpendicular to the optic axis of the crystal remaining on its surface.

polariser) but will be transmitted by the analyser when ϕ is odd multiples of π. Thus for no transmission of light through the analyer, we get

$$\phi = \frac{2\pi}{\lambda} x\alpha (\mu_e - \mu_o) = 2n\pi$$

or, $$x = \frac{n\lambda}{\alpha (\mu_e - \mu_o)} \qquad \cdots \qquad \cdots \quad (7.20a)$$

If x' be the distance of next dark fringe from the edge of the wedge then in a similar manner we get,

$$x' = \frac{(n+1)\lambda}{\alpha (\mu_e - \mu_o)} \qquad \cdots \qquad \cdots \qquad \cdots \quad (7.20b)$$

The distance between two consecutive dark bands will then be given by.

$$\beta = x' - x = \frac{\lambda}{\alpha(\mu_e - \mu_o)} \qquad \cdots \qquad \cdots \quad (7.20c)$$

Similarly if y and y' be the distance of two consecutive bright bands from the edge of the wedge we may write,

$$y = \frac{(2n+1)\lambda/2}{\alpha(\mu - \mu_o)} \text{ and } y' = \frac{(2n+3)\lambda/2}{\alpha(\mu_e - \mu_o)} \qquad \cdots \quad (7.20d)$$

Hence the distance between two consecutive bright bands is,

$$\beta' = \frac{\lambda}{\alpha(\mu_e - \mu_o)} \qquad \cdots \qquad \cdots \qquad \cdots \quad (7.20e)$$

Thus the dark and bright bands observed after transmission through the analyser will be equispaced.

White light effect :— the incident light be white then λ will be different for light of different colours which will make β or β' different for different colours. Thus all the bands will be coloured excepting the band at the edge at which $\alpha = 0$. At the apex or edge of the wedge we shall get darkness.

6.21. **Meaning of the terms 'Optical activity' and its demonstration.**

Optical activity.—If a plane-polarised light be made to pass through some substances, then it will be found that the

direction of vibration of the emergent light is not the same as that of incident light. The direction of vibration of the incident light has rotated by a certain angle, after being transmitted through the substance. This phenomenon is called **Optical activity or Rotation of the plane of polarisation** and the substance which   es the direction of vibration of the incident polarised light is called *optically active substance.*

There are two classes of active substances. One class of substance rotates the line of vibration of the incident light towards right and the substances belonging to this class are called Dextro-rotatory substances. Another class of substance rotates the line of vibration towards left and the substances which belong to this class are called Laevo-rotatory substances.

Demonstration.—If we take two crossed Nicols whose principal planes are at right angles to each other, then the field of the analysing Nicol (*i.e.* the second Nicol) would be dark. The light passing through the first Nicol, *viz.*, the polariser will be polarised whose vibration will be parallel to the principal plane of the polariser. This light will be refused transmission through the second Nicol, *viz.*, the analyser whose principal plane is perpendicular to the direction of vibration of the polarised light coming out of the polariser. If now a quartz crystal cut perpendicular to its axis is put between the crossed Nicols, then the field of the analyser at once becomes bright. This shows that the direction of vibration of the polarised light incident on the quartz, after transmission, has rotated by a certain angle and has taken up a new direction of vibration. A component of this new vibration parallel to the principal plane of the analyser passes through it and makes the field of the analyser bright. If the analyser is now rotated by a certain angle either towards right or towards left, then the field becomes dark again and at this stage, the principal plane of the analyser again becomes perpendicular to the new direction of vibration of the emergent light from the quartz. This

angle of rotation of the analyser is a measure of the rotation of the plane of polarisation by quartz crystal. If the analysing Nicol is rotated towards right, to make the field dark, then the substance is called *dextro-rotatory*. But if the analysing Nicol is rotated towards left, to make the field dark, the substance is called *Laevo-rotatory*.

7.22. Biot's laws : Meaning of specific and molecular rotation.

Biot made a systematic study of the natural rotation of the plane of polarisation by different substances, and established the following laws :—

(1) The angle (θ) of rotation produced by an active substance is proportional to the length (l) of the substance traversed by the ray and is not affected by turning the substance around, consequently the rotation will be annulled if the ray is reflected back through the substance,

Or, $\theta \propto l$, when the active substance employed is remaining the same.

(2) The combined rotation produced by two different substances having different thicknesses is the algebraic sum of the rotation caused by each separately.

(3) The amount of rotation (θ) in the case of a solution, is proportional to the amount of active substance (m) present per c.c. of the solution.

Or, $\theta \propto m$, when the length l of the solution is constant.

(4) The amount of rotation varies with the wavelength of the incident light and with temperature of the substance. The rotation is approximately proportional to the inverse square of the wavelength, but there is no definite law regarding the variation of rotation with temperature.

In the case of a solution, the first and third laws may be combined to have the relation, $\theta = slm$, where s is a constant and is called **Rotatory power** or **Specific rotation** of the solution. Thus specific rotation of a solution is defined as the amount of rotation produced by a solution of 1 decimeter in length (when $l = 1$) containing 1 gm. of the active substance per c.c. of the solution (when $m = 1$). As rotation depends on temperature and wavelength of light, the temperature and wavelength of light (usually 5893Å) used in finding s should be stated. In the case of quartz for which the rotation is very large, specific rotation is defined as the rotation produced by a 1-mm. plate.

Molecular rotation is obtained by taking the product of the specific rotation and the molecular weight of the substance.

Thus, **molecular rotation** is the rotation produced by a solution of 1 decimeter in length containing 1 gm.-molecule of the active substance per c.c. of the solution.

The experimental determination of s will thus help us in finding the molecular rotation.

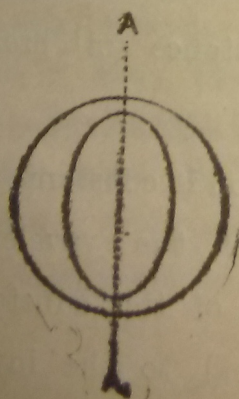**7.23.   Fresnel's explanation of the rotation of the plane of polarisation by an optically active substance.**

Fig. 7T

According to Fresnel, the optical activity shown by quartz when light travels along its optic axis (AA_1) is due to the fact that the sphere and spheroid of O-ray and E-ray respectively do not touch each other along the optic axis [Fig. 7T]. As a result the two equal and opposite circular vibration, to which the incident linear vibration is resolved at incidence travel along the axis with unequal speed.

On emergence from the crystal, the two circular vibrations will differ in phase (by ϕ, say) and they will again combine to form a linear vibration whose direction will make a certain angle (say $\phi/2$) with that of incident vibration [7U(b)]. This can be explained as follows :—

Let the incident linear vibration, which is occurring along YY' [Fig. 7U(a)], be represented by, $y = 2a \cos \omega t$.

Fig. 7U(a)

This is equivalent to a left-handed circular motion of P_2 given by,

$$\left. \begin{array}{l} y_1 = a \cos \theta = a \cos \omega t \\ x_1 = -a \sin \theta = a \cos (\omega t + \pi/2) \end{array} \right\} \quad \dots \quad (7.23a)$$

and also a right-handed circular motion of P_1 given by,

$$\left. \begin{array}{l} y_2 = a \cos \theta = a \cos \omega t \\ x_2 = a \sin \theta = a \cos (\omega t - \pi/2) \end{array} \right\} \quad \dots \quad (7.23b)$$

Suppose the right-handed circular motion travels faster within the active substance than the left-hand one. Hence, on emergence from the substance we get,

$$\left. \begin{array}{l} y_1' = a \cos \theta \; ; \\ x_1' = -a \sin \theta \end{array} \right\} \quad (7.23c)$$

[for L-motion]

$$\left. \begin{array}{l} y_2' = a \cos (\theta + \phi) \; ; \\ x_2' = a \sin (\theta + \phi) \end{array} \right\} \quad (7.23d)$$

[for R-motion]

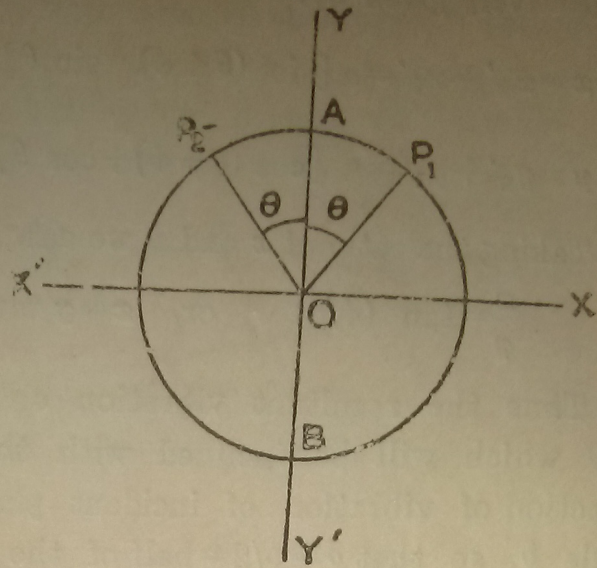Here ϕ represents the gain of phase of R-motion over that of L-motion [Fig. 7U(b)]. Thus the resultant
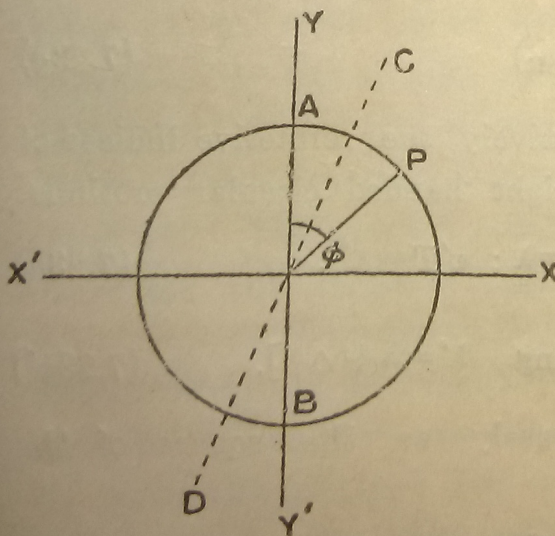

Fig. 7U(b)

vibrations along the x and y directions, on emergence are respectively given by,

$$x = x_2' + x_1' = a [\sin (\theta+\phi) - \sin \theta] = 2a \cos \left(\theta + \frac{\phi}{2}\right) \sin \frac{\phi}{2}$$

$$y = y_2' + y_1' = a [\cos (\theta+\phi) + \cos \theta] = 2a \cos \left(\theta + \frac{\phi}{2}\right) \cos \frac{\phi}{2}$$

Taking the ratio of x and y we get,

$$\frac{x}{y} = \tan (\phi/2) \qquad \text{or,} \quad x = y \tan (\phi/2) \qquad \cdots \qquad (7.23e)$$

Thus the resultant vibration on emergence is linear along CD which will be inclined with the y-axis (which is the direction of vibration of incident plane-polarised light) by an angle δ, so that $\delta = \phi/2 =$ half of the phase difference ϕ between the two emergent circular vibrations [Fig. 7U (b)].

If v and v' be respectively the velocities of the left and right handed circular motion within the active substance $(v' > v)$ then their time-difference $= t = (l/v - l/v')$ [where $l =$ thickness of active substance].

∴ Phase difference between the two circular vibrations is given by, $\phi = \frac{2\pi l}{T}\left(\frac{1}{v} - \frac{1}{v'}\right)$. [∵ for periodic time-difference T, the phase difference is 2π.]

Rotation of the vibration $= \delta = \phi/2 = \frac{\pi l}{T}\left(\frac{1}{v} - \frac{1}{v'}\right)$ $\qquad (7.23f)$

or, $\delta = \frac{\pi l}{cT}\left(\frac{c}{v} - \frac{c}{v'}\right) = \frac{\pi l}{\lambda}(\mu_L - \mu_R)$ $\qquad \cdots \qquad (7.23g)$

Here, μ_L and μ_R are respectively the refractive indices of the active substance for left and right handed circular motions.

or, $\delta = \pi l \left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)$ [∵ $vT = \lambda$; $v'T = \lambda'$]. $\qquad (7.23h)$

or, $\delta = \frac{\pi l \, \Delta\lambda}{\lambda^2}$ approx. [Taking, $\lambda' = \lambda + \Delta\lambda$]. $\qquad (7.23h')$

Thus rotation, varies inversely as the square of the wavelength λ.

Verification of Fresnel's theory :—To prove that the linear vibration of a plane-polarised light is resolved into two equal but opposite circular motions on entering an active subs-

tance, Fresnel arranged a number of right-handed and left-handed prisms of quartz alternately, so as to form a parallelopiped [as shown in Fig. 7U (c). In all these prisms, the optic axis was kept parallel to the base of the prisms, i.e. parallel to the axis of parallelopiped.
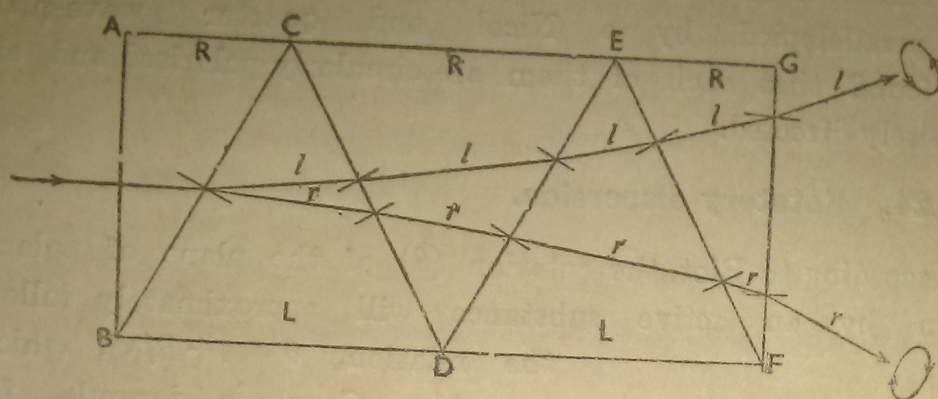

Fig. 7U(c)

Now a right-handed circular motion travels faster in a right-handed prisms but slower in a left-hand prism. Hence if a right-handed circular motion enters a left-handed quartz prism its motion will be slower and it will be deviated towards the normal but when it enters a right-handed quartz prism, its motion will be faster and it will be deviated away from the normal.

Suppose the linear vibration of a plane-polarised light is incident normally on the face AB of the right-handed quartz prism ABC. This linear vibration will be resolved into two equal but opposite circular vibrations which will travel along its optic axis with unequal speed so that the speed of R-motion is greater than that of L-motion. These two circular motions when enter the second left-handed prism BCD, the speed of L-motion will increase while that of R-motion will decrease. As a result, L-motion will be deviated away from normal while R-motion will be deviated towards the normal causing a separation between the two circular motions.

Again when these two circular vibrations enter the third right-handed prism CDE, the speed of R-motion will increase while that of L-motion will decrease, due to which R-motion will be deviated away from normal while L-motion will be deviated towards the normal. By this, the two circular

vibrations will be further separated. Thus by each prism, the two components will be separated more and more. If a large number of such prisms are employed, the R-motion and L-motion will be completely separated.

Fresnel examined each of the components emerging from the parallelopied by a Nicol and quarter wave-plate and found that each of them are circularly polarised and are oppositely directed.

7.24. Rotatory dispersion.

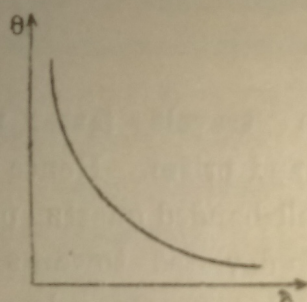According to Biot, the rotation (θ) of the plane of polarisation by an active substance will approximately follow the relation, $\theta = A + B/\lambda^2$, which resembles Cauchy's formula for normal dispersion. The relation between θ and λ can be graphically represented by a curve the nature of which is shown in Fig. 7 V.

Fig. 7V

Suppose a light of wavelength λ from an illuminated slit S_1 is made parallel by a lens L_1 and is then polarised by a Nicol P whose shorter diagonal is kept vertical (Fig. 7W). Thus the vibration of the light from P will be vertical. This light is then cut off by another Nicol A (analysing Nicol) whose shorter diagonal is therefore horizontal. Thus no light will pass out of the lens L_2 and the screen S_2 will remain dark.
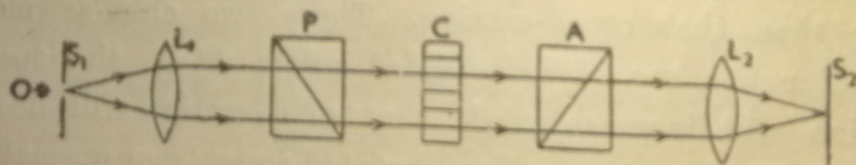

Fig. 7W

If now a quartz crystal C, whose axis is perpendicular to the surface, be interposed between P and A, then the polarised light from P will travel along the optic axis of C. After emergence from C the vibration of the polarised light will rotate by an angle θ and a component OE_1' of this rotated vibration will enter the analyser A and will be converged