Polarization (Optics)

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B.Sc Part-II
Paper-III

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Polarization

The phenomenon of diffraction and interference of light show that the light wave may be longitudinal and transverse in nature. To explain the phenomenon of polarization it is required that the light wave is a transverse wave.

In an ordinary beam of light with millions of waves, the light vectors of component waves will remain in all possible direcn on a plane drawn at a right angle to the direcn of propagation. This happens due to random orientations of excited atoms or molecules in the source. Such an ordinary beam of light with the electric vectors arranged symmetrically about the direcn of propagation is called an ~~upola~~ unpolarized light. If by some means one of these rectangular vibrations is cut off we get vibrations of all the component waves confined in one definite direcn, such a light is said to be plane polarised light.

The electric vector of a plane polarized light is confined to a particular plane known as the

plane of vibration. This plain contains the $\vec{E}$ & the propagation vector $\vec{K}$.
The plane ⊥r to the plane of vibration is known as plane of polarization.

If the magnitude of the resulting light vector (superposition of two plain polarized wave) remains const the tip of the light vector appears to trace out a circle at a fixed space. Such a light is said to be circularly polarized. If on looking towards the incoming light the resultant light vector appears to rotate clock-wise, then the light is said to be right circularly polarized light.

If the light rotates counter clockwise then the light vectors is said to be left circularly polarized light.

If the magnitude of resulting light vector varies periodically between a max. and min. value, then the tip of the light vector appears to trace out an elliptic path. Such a light is said ~~to~~ be elliptically polarized.

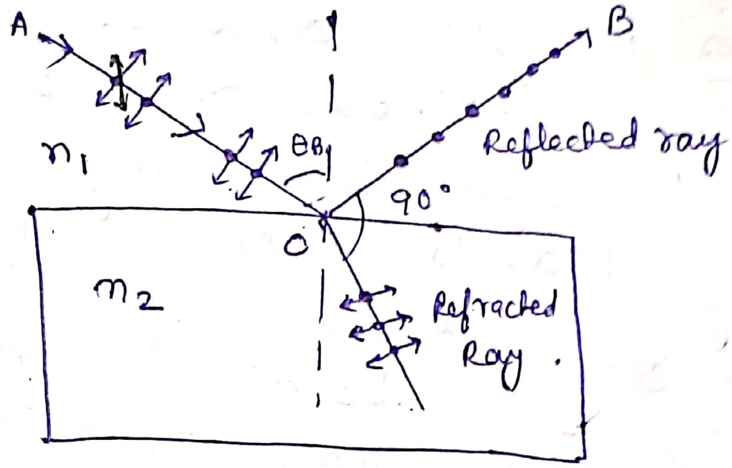
A mixture of polarized and unpolarized light is called partially polarized light.

Brewster's Law :→ If an ordinary beam of light is incident on a glass plate at a particular angle θ_B it is found that the reflected light becomes almost totally plane polarized light. The plane of vibration being $\perp^r$ to the plane of incident. For angles other than θ_B the reflected light is partially polarised. This particular angle of incidence at which the reflected light is almost totally polarized is called the angle of polarization of the given surface. It depends on the nature of the reflecting medium and wavelength of the light.

At polarizing angle (θ_B) the reflected & refracted rays are 90° apart. Therefore angle of refraction $= 90^\circ - \theta_B$.

$$\therefore \frac{n_2}{n_1} = \frac{\sin\theta_B}{\sin(90^\circ - \theta_B)} = \tan\theta_B .$$

Thus the tangent of the angle of polarization is equal to the refracting ~~medium~~ index of the reflecting medium. This is known as Brewster's law.



Polarization by Refraction

If a beam of ordinary light (unpolarized) is incident on a glass plate at the a polarising angle (θ_B) ~~for glass~~, the transmitted light will be partially plane polarized though the reflected light will be almost totally plane polarized. If a number of $\|^{l}$ glass plates are used then at each reflection the rays whose vibrations are $\perp^r$ to the plane of incidence are reflected. The transmitted light contains the vibration in the plane of incidence and a reduced amount of vibration $\perp^r$ to the plane of incidence. Thus a large no. of $\|^{l}$ plates transmitted light losses more and more $\perp^r$ vibrations at each reflection and ultimately becomes totaly polarized whose vibration remains in the plane of incidence. This arrangement is known as piles of plates.

Optic axis → optic axis of a crystal is defined as the direction through it along which if a ray travels then there will be no double refraction the ordinary of the ray and both travel with and extraordinary ray this direction. equal velocity along

A double refracting crystal possesing only one optic axis is called uniaxial crystal.

example → (i) Calcite, $CaCO_3$ * Hydrate calcium carbonate → calcite (uniaxial)
(ii) quartz.

Principal section → Principal section of a crystal is its section by a plane which passes through the optic axis of the crystal and is ⊥r to its two opposite refracting faces.

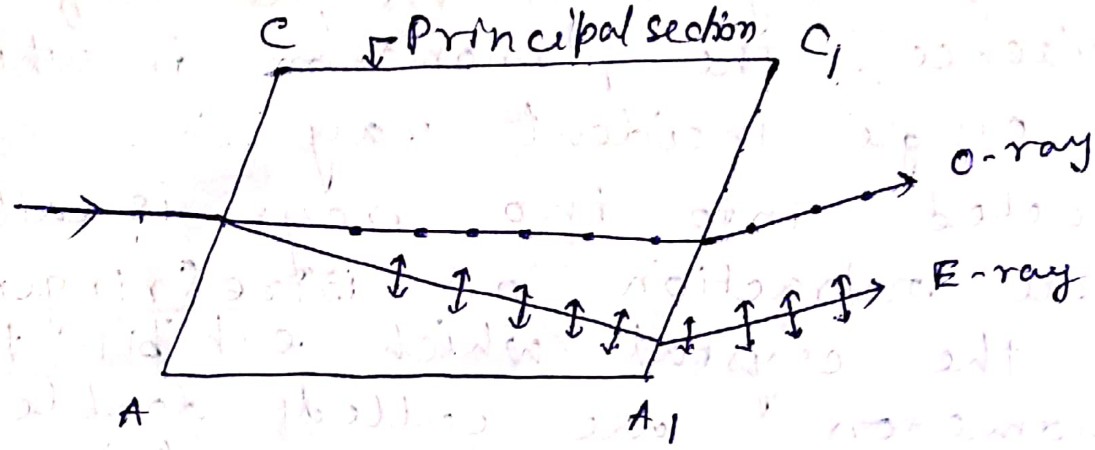
Double Refraction: There are several crystal in which the simple laws of refraction are not followed. We found that in this crystals

1) There are two refracted rays for each incident ray.
2) The two refracted rays may

not generally lie in the plane of incidence. The phenomenon in which a single incident ray is refracted into two rays is called double refraction or Birefringence and the crystal which exhibit the phenomenon are called double refracting crystal or Birefringent. Those crystal in which the double refraction occurs ~~not~~ is said to be optically anisotropic. Anisotropic means not having identical properties in different directions.

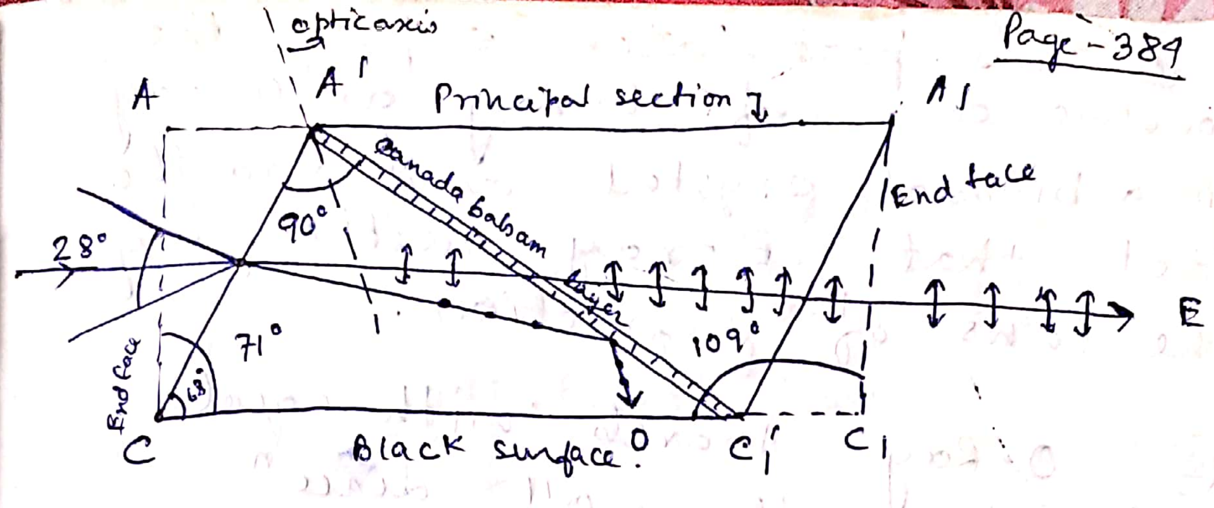
In some anisotropic crystalline media one of the two refracted rays obeys the laws of refraction the ordinary of light and is called the other ray ray (O-ray) while the laws of refraction does not obey the extra- of light and is called the ordinary ray (E-ray). Both of these E-ray and O-ray are plane polarized whose vibrations are along and at right angles to the principle sections.

When both the refracted rays disobey the laws of refraction the crystal is called a bi-axial crystal.



Nicol Prism

Nicol prism is an optical device designed from calcite and is used for the production and analysis of plane polarised light. A beam of ordinary light entering the calcite crystal breaks up into the E-rays and O-rays by double refraction. The O-ray is cut off by total internal ~~reflection refraction~~ reflection while the E-ray is allowed to pass through. Figure shows a properly cut calcite crystal in which a layer of canada balsam has been introduced ~~sho~~ so that the ordinary ray undergoes total internal reflection. The extraordinary component passes through and the beam emerging from the crystal is linearly polarized.



Huygens's theory of double refraction and the nature of wave surfaces in uniaxial crystal :-

With the idea of secondary wavelets Huygen gave a satisfactory explanation of phenomenon of double refraction in uniaxial crystal. For uniaxial crystal the phenomenon of double refraction was explained by Huygen on the basis of following postulates —

(1) Every pt. of a double refracting crystal distributed by the incident light becomes the source of two secondary wavelets — spherical for O-ray and ellipsoid of revolution about the optic axis for E-ray.

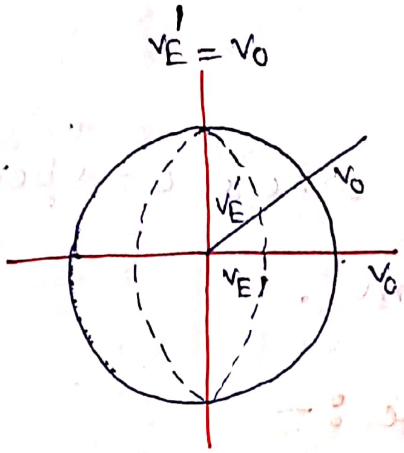
(2) The O and E wavelets touch along a particular ~~axis~~ direcn, which is fixed called optic axis, relative to the crystallographic axes.

① This postulates explain the occurance of E ray and O-ray in a biaxial crystal and also the fact that E-ray neither obey the laws of refraction.

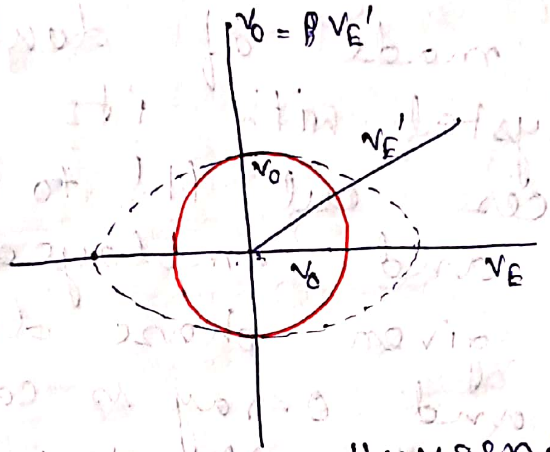
② O-Ray travels with equal velo. in ~~ally~~ all direc^n

③ Along the optic axis O-ray and E-ray travel with equal velo. and there is no double refraction.

The nature of the secondary wave surfaces is shown in the fig. in which crystal like calcite in which O-ray travels with smaller velo. than E ray ~~xxx~~ in the direc^n normal (i.e $n_e < n_o$) to the optic axis are called negative crystals. Crystal like quartz in which O-ray travels with greater velo than E ray in the direc^n normal ($n_e > n_o$) to the optic axis are called positive crystal.



(a) Positive crystal
VE < Vo. Exam – quartz, ZnO.
$n_e > n_o$



(b) Negative crystal.
VE > Vo ; ex → calcite.
$n_o > n_e$

Fig. shows Huygens' wave surfaces in unit time. In fig (a), the O wave surface is outside the E wave surface (positive crystals). In fig (b), the E wave surface is outside the O wave surface ((–)ve crystal). The velo. Vo is the same in all direc^ns. The velocity VE' for E waves has one limit VE' = Vo along the optic axis and the other limit VE' = VE for any direc^n in a plane ⊥r to the optic axis. It is this extreme value VE which is called the extra-ordinary wave velocity.

We now define the R.I. of ordinary and extraordinary uniaxial crystal

$$n_o = \frac{c}{V_o}$$

$$n_e = \frac{c}{V_E}$$ where c = speed of light in vaccum.

Retardation plate :-

A plate made of double refracting crystal, with its refracting faces cut ∥ to the optic axis and employed to introduce a given phase diff. betn E ray and O-ray is called a retardation plate. If d be the thickness of the plate n_o and n_e be the R.I. for O ray and E ray then the path diff. introduce by the plate is given by

$(n_o \sim n_e) d$. Corresponding phase diff. given by

$$\delta = \frac{2\pi}{\lambda} (n_o \sim n_e) d.$$

If the thickness d of the plate is such that a path diff of $\frac{\lambda}{4}$ or a phase diff of $\frac{\pi}{2}$ is introduced betn O ray & E ray, then the plate is called a quarter wave plate.

The thickness of the quarter wave plate is given by

$$(n_o \sim n_e) d = \frac{\lambda}{4}$$

$$\text{or, } d = \frac{\lambda}{4(n_o \sim n_e)}$$

If the thickness d of the plate is such that a path diff. of $\frac{\lambda}{2}$ or a phase diff. π is introduced betn O ray & E ray then the plate is called a half wave plate.

The thickness of a half wave plate is given by $(n_o \sim n_e) d = \frac{\lambda}{2}$

$$\text{or, } d = \frac{\lambda}{2(n_o \sim n_e)}$$

Optical Activity → If a plane polarized light is passed through some crystal like quartz along the optic axis, the plane of vibration gradually undergoes rotation about the optic axis. The angle of rotation is found to depend on the thickness and the nature of the crystal and also of the wavelength of light employed. This phenomenon is called optical activity or rotatory polarization.

and the substances which rotates in the direcn of vibration of the incident polarized light is called optically active substance.

There are two classes of optically active substances.

one class of substance rotates the line of vibration of the incident light towards right and the substances belong to this class are called ~~dexorotatary~~ dextrorotatory substances.

Another class of substances rotates the line of vibration towards left and the substances belonging to this class are called Laevorotatory substances.

Dextrorotatory – Cane sugar, Rochelle salt, d-glucose, quartz.

Laevorotatory – α – fructose, nicotine,

Analysis of Polarised light :-

From the pt. of view of polarization a given beam of light may be

(1) unpolarized.
(2) Partially Polarized
(3) Plane "
(4) circularly "
(5) Elliptically "

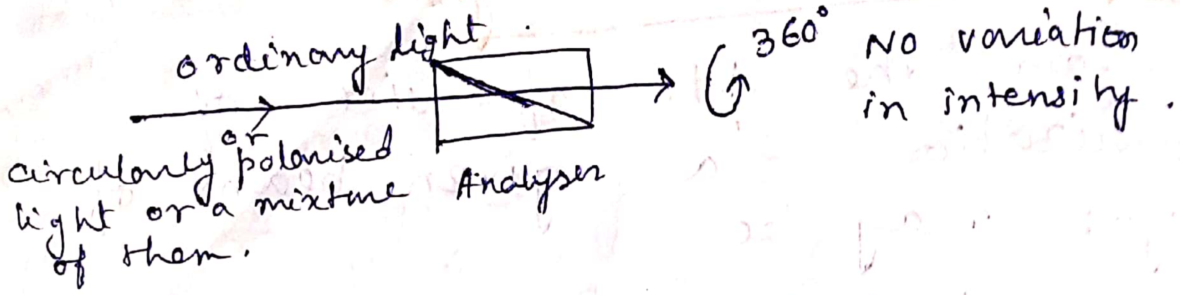
Let us now apply the test and ~~ap~~ analize the observation —

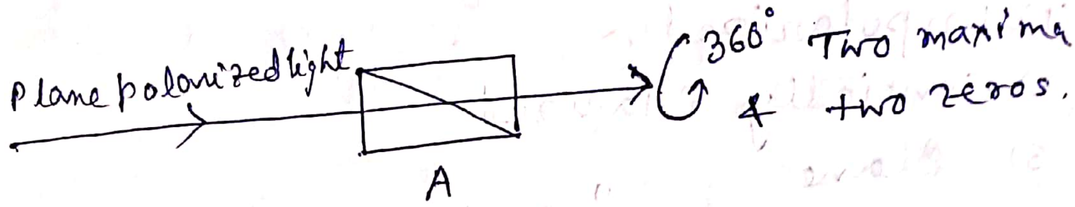
Test A :— Pass the beam through a nicol and note the changes of intensity as the nicol is rotated.

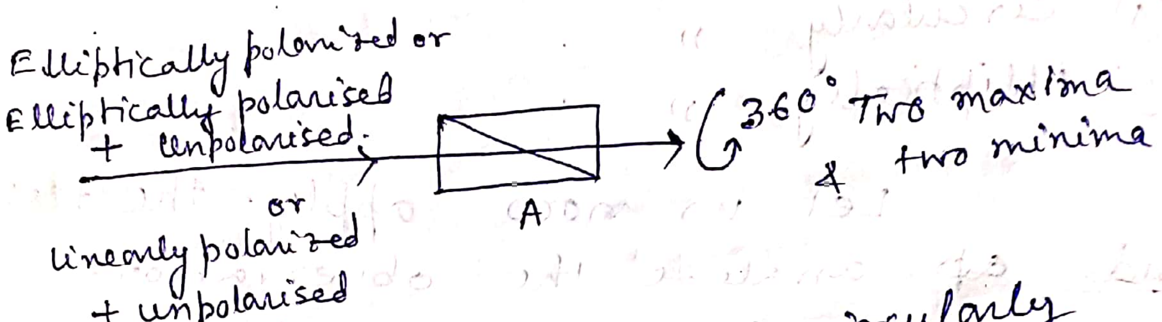
observation 1 :→ No change of intensity what so ever. The beam must be either unpolarized or circularly polarized.

Obs. 2 :→ Intensity shows variation — Two maxima and two minima in one rotation but minimum intensity is not zero. The beam must be partially plane polarized or elliptically polarized.

obs. 3 :→ Intensity shows variation and the min. intensity is zero. The beam must be plane polarized.



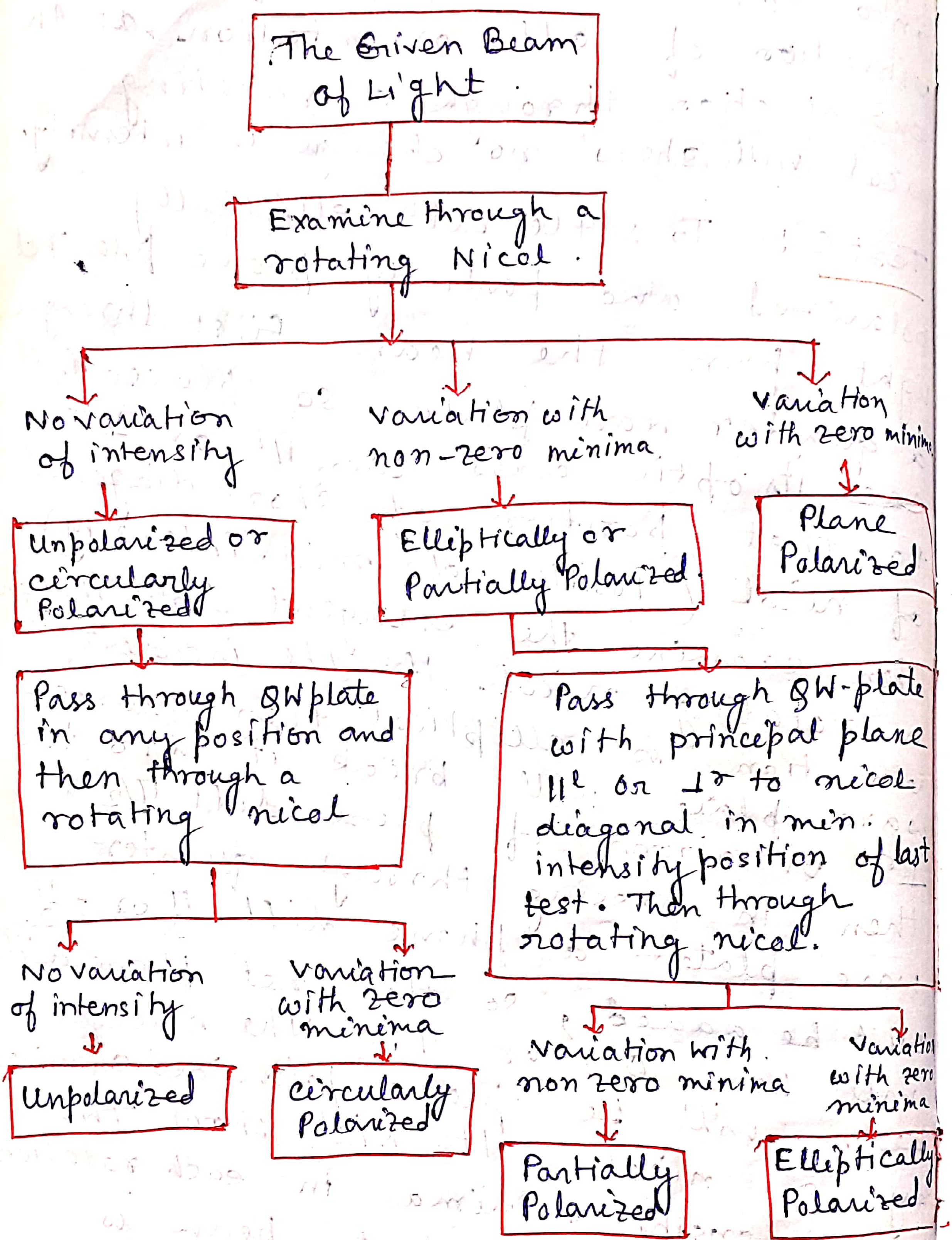




Test B → To settle betn circularly polarized and unpolarized light pass the beam through a 1st quarter wave plate (λ/4 plate) and then examine the beam is through a nicol. If the beam is circularly polarized the quarter wave-plate will break it into two ⊥r vibration with phase diff π/2, then in passing through the plate a further phase diff π/2 or − π/2 will be created betn them, so that the two emergent ⊥r vibrations will have phase diff. 0 or π. Either case their resultant will become plane polarized vibrations. So on rotating the analysing nicol there will be two positions of zero intensity. These ~~to~~ will show that the incident beam is circularly polarized : If the original beam is unpolarised then the infinite no. of plane of vibrations of all orientation will be converted by the QW plate into an infinite set of elliptical vibration of all orientation. An examination through a rotating nicol will show no change in intensity.

Test C :- To settle betn elliptically polarized and partially plane polarized light pass the beam first through a quarter wave plate so placed that ~~each~~ its optic axis lies ∥ or ⊥r to that position of short diagonal of nicol (position of min. intensity) Then examine the emergent light through a rotating nicol. If the incident vibration is elliptical then quarter wave plate will break it into two ⊥r vibrations of phase diff π/2, then in passing through quarter wave plate a phase diff $\frac{\pi}{2}$ or $-\frac{\pi}{2}$ will be added, so the net phase diff. will be 0 or π. The emergent beam will be plane polarized examined by a nicol. It will show two zero intensity minima in each rotation.

If the incident beam is partially polarized each of its vibration will be converted by a quater wave plate into an elliptical vibration and examination through a nicol will show variation of intensity with non zero min.



***Faraday Effect :→** Faraday discovered that if a block of glass is placed in a strong mag. field it becomes optically active. When a plane polarized light is passed through it in a direc^n ∥ to the mag. field the plane of vibration undergoes rotation. This phenomenon is known as <u>Faraday Effect</u>.

The angle of rotation of the plane of vibration (θ) is found to be proportional to the mag. field $\vec{B}$ and to the distance l, the light travels through the medium

$$\theta = VBL.$$

V is a const known as verdet's const. It may be defined as the rotation per unit path per unit mag. field. The rotation θ is said to be (+) ve if the direc^n of rotation occur in the direc^n of circulation of current which will give mag. field in the direc^n of $\vec{B}$.

Kerr Effect → Kerr discovered that some transparent substances which are otherwise isotropic become doubly refractive under a strong electric field. As a result they rotate the plane of polarization of light passing through them. This effect is called Kerr effect (Kerr electro-optic effect). When a plane polarized beam of light falls on the polished of an electromagnet, the plane of polarization of the reflected light is not the same when the ~~electro~~magnet is on as it when the magnet is off. This effect is called Kerr magneto-optic effect.

Kerr cell :- It is small glass cell ~~of~~ filled with pure nitro-benzene in which two metal plates shield with their surfaces vertical & ||ˡ to each other. This cell is placed betⁿ two crossed nicols or polaroid. In absence of any electric field betⁿ ~~dig~~ the plate light can't pass out of 2nd nicol. But when a Potential difference is applied betⁿ the plates nitrobenzene will behave as a doubly reflecting crystal having its axis ||ˡ to electrical field. Hence plane polarized light from 1st nicol will be elliptically polarized after its passage through the Kerr cell, when the direcⁿ of vibration of polarised ~~(e)~~ light is not ||ˡ or ⊥ʳ to the electric direcⁿ of force.

Function of a Nicol Prism :-

A nicol prism can be used as a polariser and also used as a analyser of a linear polarised light.

As a polariser :- An incident ray falling on one of the end faces of the nicol and moving in a direcⁿ nearly ||ℓ to its length is divided into O-ray and E-ray whose vibrations are ⊥ʳ & ||ℓ to the principale section of the nicol. The geometry of nicol prism is such that O ray is incident on the canada balsam layer at an angle greater than the critical angle and therefore totally reflected. This totally reflected light is passed out through the side of the prism and is absorbed by the lamp black layer on the sides of the prism.

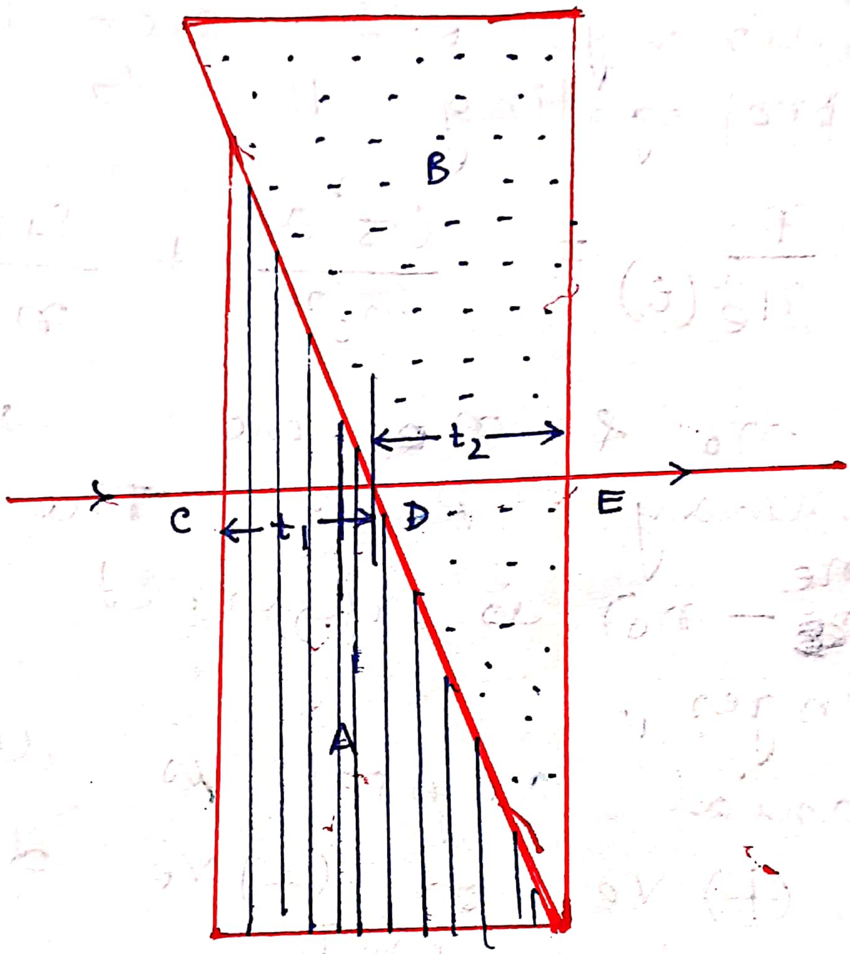
For E-ray canada balsam layer is optically denser than the calcite and the E ray is freely transmitted and emerges out of the opposite end face. Thus we get a plane polarised light whose vibrations are ||ℓ to the plane of incidence. for total reflection of O-ray the angle of incidence at the canada balsam layer does not exist 14°.

As an analyser :- To analyse a linearly polarised light we would require to get information about the plane of vibration of the plane polarised light.

Suppose a plane polarized light be made incident on one face of a nicol so that the direcⁿ of its vibration of amplitude a makes an angle θ with the principle section of the nicol. This vibration of amp. of 'a' will be resolve into vibration of amp. $a\cos\theta$ & $a\sin\theta$ ∥ˡ & ⊥ʳ to the principle section of the nicol. The component $a\cos\theta$ which is ∥ˡ to the principle section will be freely transmitted as E-ray and the component $a\sin\theta$ which is ⊥ʳ to the principle section of the nicol will behave as O-ray and will be cut off by the total reflection from the canada balsam layer. If the nicol is rotated with the incident ray as axis, value of θ will change. When $\theta = 0$, the amp. of transmitted component will be 'a'. and the E-ray which is freely transmitted by the nicol becomes most intensed at any amp. 'a'. When $\theta = 90°$, the E-ray has its amp. zero and so the field becomes completely dark.

If the incident light be unpolarized then for any position of the nicol the vibrations of the incident light can be resolved ∥ˡ & ⊥ʳ to its principle sections. The ∥ˡ component will pass through the nicol and the ⊥ʳ component will be refused transmission.

Babinet's compensator :-



Babinet's Compensator :

A quarter wave plate or half wave plate produces only a fixed path difference betn the ordinary and extra-ordinary rays and can be used for light of a particular wavelength. For different wave length diff. quarter wave plate are to be used. To avoid this difficulty Babinet designed a compensator by means of which a desired path diff. can be introduced.

It consist of a two ~~wage~~ wedge shaped sections A & B of quartz. The optic axis is length wise in A and transverse in B. The outer faces of the compensator are ||e to the optic axis. Therefore the O-ray & E ray travels ~~alon~~ with diff. velocities along the same direcn inside the compensator. The E-ray in A behaves as O-ray in B and the O-ray in A behaves as E-ray in B. Suppose a plane polarized ||e beam ~~is~~ of light is incident normally at the pt. C of the babinet compensator. The beam is split up into E ray & O-ray.

The path diff. introduce betn them after they have traveled a distance CD in A is $(\mu_e - \mu_o) t_1$. In B, E-ray behave as O-ray and vice-versa. Therefore the path diff. introduce in B is

$(n_o - n_e)t_2$. The resultant path diff

$= (n_e - n_o)(t_1 - t_2)$

Since the crystal B can slide along the surface of A, $(t_1 - t_2)$ can be made to have any desired value. Hence any path diff. can be introduced with the help of Babinet compensator and it can be used for light of any wave length.