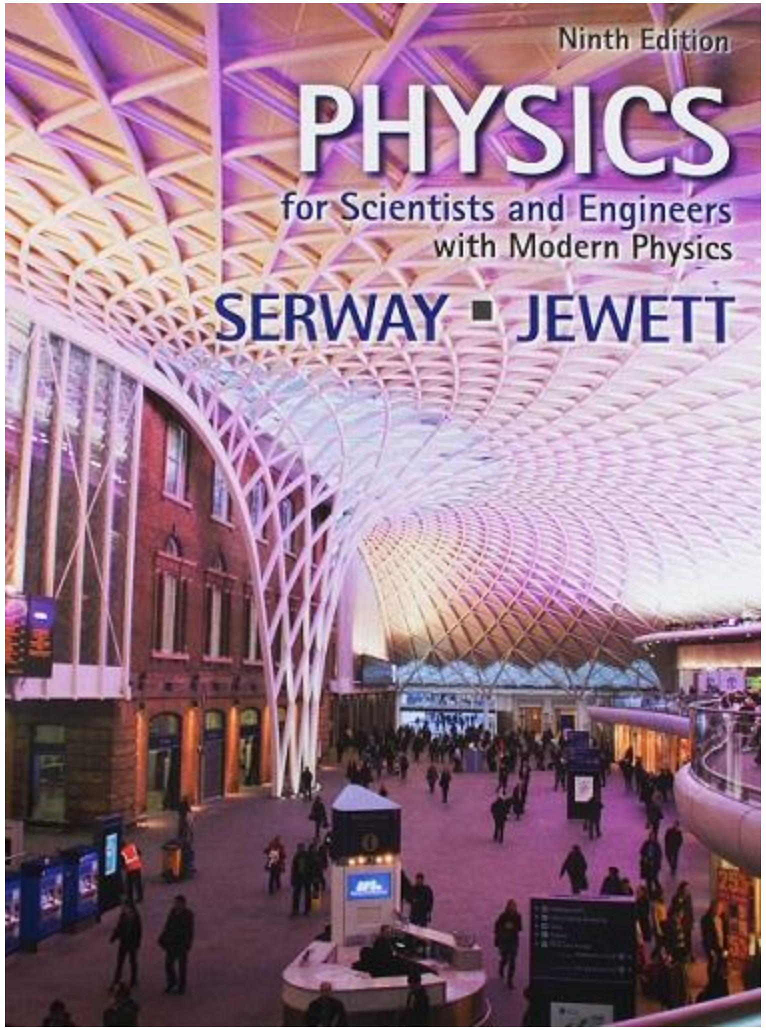
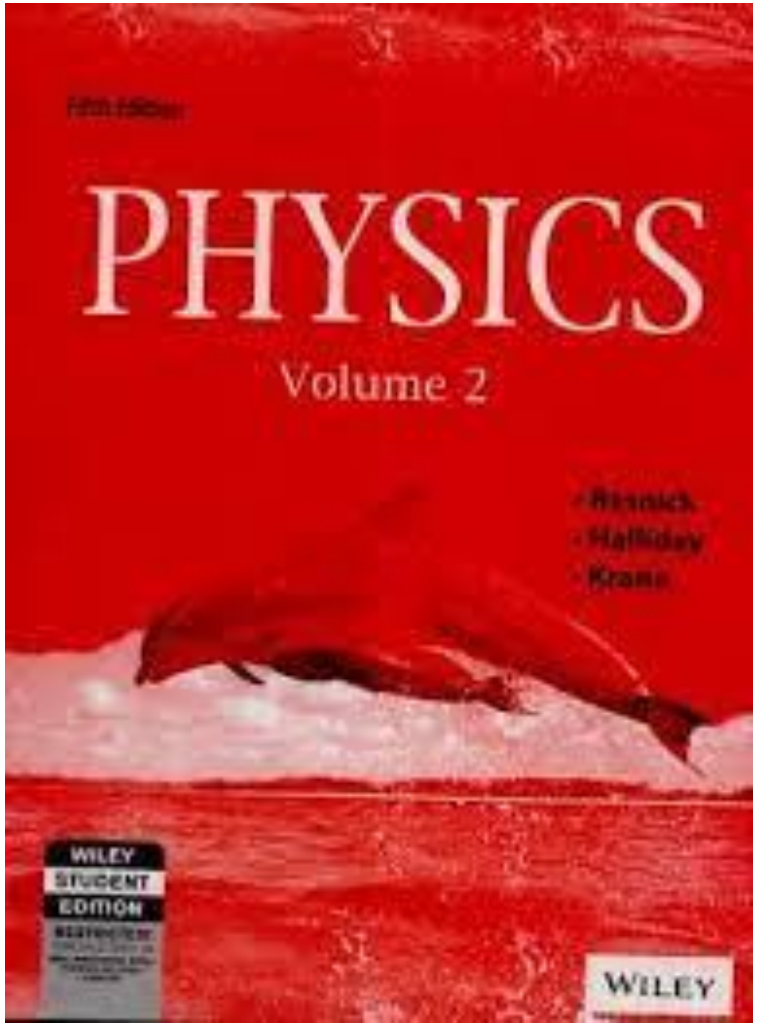
PHYSICS

General Physics I (PHYS 101)





Ganesh Kuwar Chhetri

Dept. of Physics, School of Science, Kathmandu University

POLARIZATION

Course Outline

- Polarization
- Polarization by Reflection
- Brewster's Law, Mauls' Law
- Double Refraction
- Nicol Prism as Polarizer and Analyzer
- Optically Active Substances & Specific Rotation

Polarization

Light

- Light is an electromagnetic wave.
- A light wave is an electromagnetic wave whose electric field and magnetic field vectors vibrate perpendicular to the direction of wave propagation.

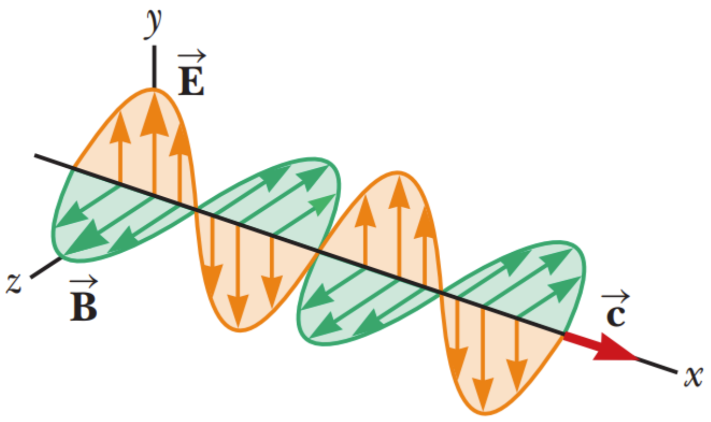


Figure P-1
Schematic diagram of an electromagnetic wave propagating at velocity c in the x direction. The electric field vibrates in the *xy* plane, and the magnetic field vibrates in the *xz* plane.

- An ordinary beam of light consists of a large number of waves emitted by the atoms of the light source. Each atom produces a wave having some particular orientation of the electric field vector $\vec{E}$, corresponding to the direction of atomic vibration. The direction of polarization of each individual wave is defined to be the direction in which the electric field is vibrating. In Figure P-1, this direction happens to lie along the *y* axis. All individual electromagnetic waves travelling in the *x* direction have an $\vec{E}$ vector parallel to the *yz* plane, but this vector could be at any possible angle with respect to the y axis. Because all directions of vibration from a wave source are possible, the resultant electromagnetic wave is a superposition of waves vibrating in many different directions. The result is an unpolarized light beam.

Polarization

Polarized Wave

- The electromagnetic waves emitted by a television station are polarized.
- VHF (very high frequency) television antennas in England are oriented vertically, but those in North America are horizontal. The difference is due to the direction of oscillation of the electromagnetic waves carrying the TV signal. In England, the transmitting equipment is designed to produce waves that are polarized vertically; that is, their electric field oscillates vertically. Thus, for the electric field of the incident television waves to drive a current along an antenna (and provide a signal to a television set), the antenna must be vertical. In North America, the waves are polarized horizontally

POLARIZATION

Polarized and Unpolarized Light

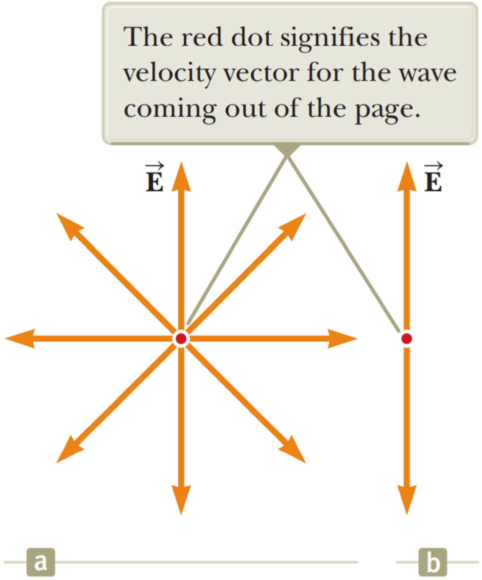


Figure P-2

(a) A representation of an unpolarized light beam viewed along the direction of propagation. The transverse electric field can vibrate in any direction in the plane of the page with equal probability.

(b) A linearly polarized light beam with the electric field vibrating in the vertical direction.

Polarization

Unpolarized Light

- In unpolarized light, the electric field vectors vibrate in all direction perpendicular to the direction of propagation.
- The electromagnetic waves emitted by any common source of light (such as the Sun or a bulb or a candle) are unpolarized.

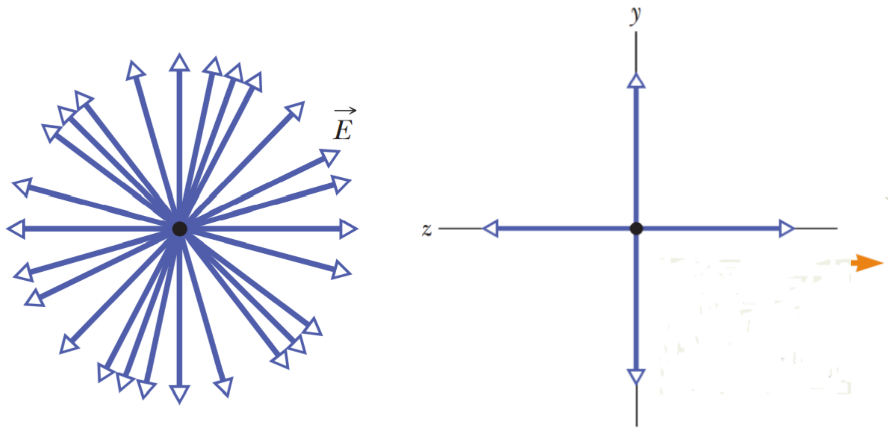


Figure P-3:
A representation of an unpolarized light beam viewed along the direction of propagation.

Polarization

- The process of confining the vibrations of the electric vector of light waves to one direction.
- Polarization is a characteristic of all transverse waves.
- It conforms the wave theory and transverse nature of light.
- **Polarization** distinguishes between longitudinal and transverse wave. Transverse waves (light waves) can be polarized where as longitudinal waves (sound waves) cannot be polarized.

Plane Polarized Light

- In polarized light, the electric field vector vibrates in one direction.

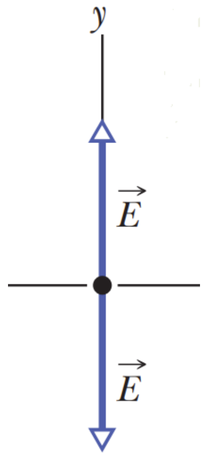


Figure P-4:
A representation of polarized light

Polarization

Plane of Polarization

- The plane formed by $\vec{E}$ and the direction of propagation is called the **plane of polarization** of the wave.

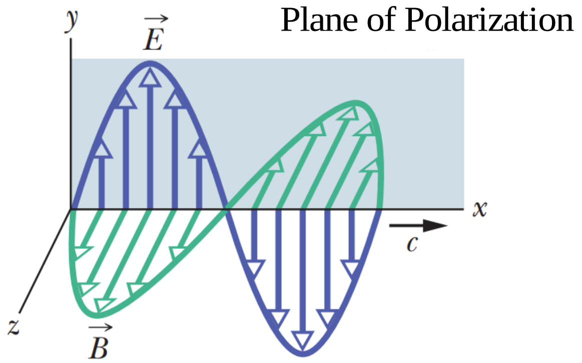


Figure P–5

An instantaneous snapshot of a travelling electromagnetic wave showing the $\vec{E}$ and $\vec{B}$ vectors

Polaroid

- We can transform unpolarized visible light into polarized light by sending it through a polarizing sheet, as is shown in Figure P-7. Such sheets, commercially known as Polaroids or Polaroid filters.
- Polaroids were invented in 1932 by Edwin Land while he was an undergraduate student. A polarizing sheet consists of certain long molecules embedded in plastic.

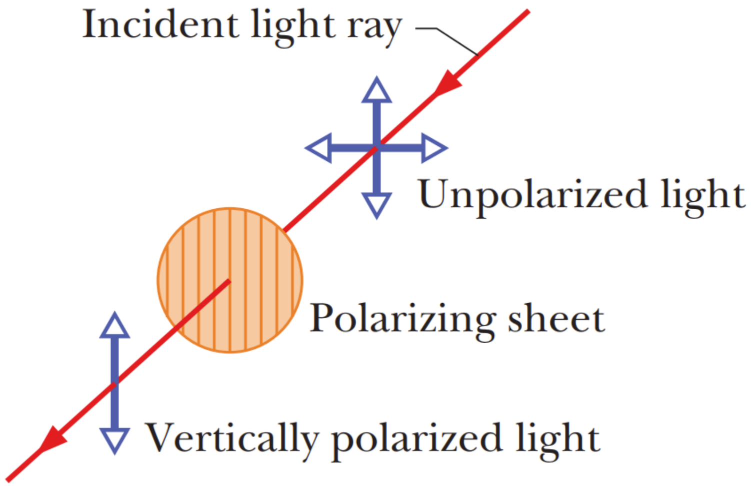


Figure P–6

Unpolarized light becomes polarized when it is sent through a polarizing sheet. Its direction of polarization is then parallel to the polarizing direction of the sheet, which is represented here by the vertical lines drawn in the sheet

Production of Plane Polarized Light

Production of Plane Polarized Light

- A linearly polarized beam can be obtained from an unpolarized beam by removing all waves from the beam except those whose electric field vectors oscillate in a single plane.

Process for Producing Polarized light from Unpolarized Light

1. Polarization by reflection

- Polarization by reflection is a common phenomenon. Sunlight reflected from water, glass, and snow is partially polarized.
- When an unpolarized light beam is reflected from a surface, the reflected light may be completely polarized, partially polarized, or unpolarized, depending on the angle of incidence. If the angle of incidence is 0^0, the reflected beam is unpolarized. For other angles of incidence, the reflected light is polarized to some extent, and for one particular angle of incidence, the reflected light is completely polarized.

2. Polarization by Double Refraction

- When unpolarized light enters a **birefringent [**Crystalline material such as calcite and quartz**]** material, it may split into an **ordinary (O) ray** and an **extraordinary (E) ray**. These two rays have mutually perpendicular polarizations and travel at different speeds through the material.

Polarization by Reflection

Polarization by Reflection

- Unpolarized light can be polarized, either partially or totally, by reflection .
- When ordinary beam of light is incident on the surface of any transparent material, the reflected beam is partially plane polarized. The reflected beam becomes completely plane polarized for a particular angle of incidence called the **polarizing angle**.
- When light is incident at the polarizing angle the reflected light is completely polarized and reflected and refracted rays are perpendicular to each other.
- Reflected light is completely polarized when the angle of incidence is such that the angle between the reflected and refracted beams is 90^0. This angle of incidence, called the **polarizing angle** , satisfies **Brewster's law**:

$$\boxed{\tan\theta_P = \frac{\mu_2}{\mu_1}} \qquad \left\{\begin{array}{l}\text{where } \mu_1 \text{ is the index of refraction of the medium in whichthe light initially travels} \\ \text{and } \mu_2 \text{ is the index of refraction of the reflecting medium.}\end{array}\right\}$$

Snell's Law

For monochromatic light and for a given pair of materials, a and b on opposite sides of the interface, the ratio of the sines of the angles θ_a and θ_b, where both angles are measured from the normal to the surface, is equal to the inverse ratio of the two indexes of refraction:

$$\boxed{\frac{\sin\theta_a}{\sin\theta_b} = {}_a\mu_b = \frac{\mu_b}{\mu_a} \Rightarrow \quad \mu_a \sin\theta_a = \mu_b \sin\theta_b}$$

Brewster's Law

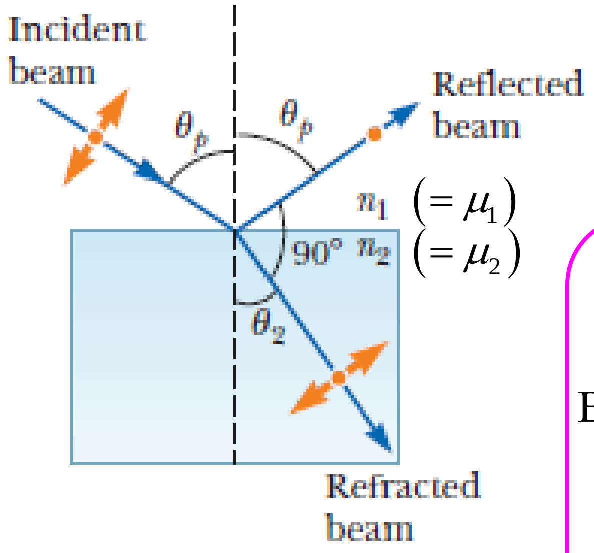
Brewster's Law

- In 1812 the British scientist **Sir David Brewster** discovered that when the angle of incidence is equal to the polarizing angle θ_P , the reflected ray and the refracted ray are perpendicular to each other (Figure Br-1).

From Figure,

$$\theta_p + 90^0 + \theta_2 = 180^0$$

$$\Rightarrow \theta_2 = 90^0 - \theta_p \quad \text{..........} \quad (1)$$



(completely polarized)

$(=\mu_1)$

$(=\mu_2)$

From Snell's law of refraction:

$$\frac{\mu_2}{\mu_1} = \frac{\sin\theta_1}{\sin\theta_2} \quad \text{..........} \quad (2)$$

or, $$\frac{\mu_2}{\mu_1} = \frac{\sin\theta_p}{\sin\theta_2} = \frac{\sin\theta_p}{\sin\left(90^0 - \theta_p\right)} = \frac{\sin\theta_p}{\cos\theta_p} = \tan\theta_p$$

(where the incident beam is in medium 1 and the refracted beam in medium 2)

$$\therefore \quad \boxed{\tan\theta_p = \frac{\mu_2}{\mu_1}} \quad \text{..........} \quad (3)$$

$$\text{Brewster's law} \rightarrow \left\{ \begin{array}{l} {}_1\mu_2 = \tan\theta_p \\ \tan\theta_p = \dfrac{\mu_2}{\mu_1} \\ \tan\theta_p = \mu \\ \qquad (\text{medium } 1 \rightarrow \text{air}) \end{array} \right\}$$

This expression is called **Brewster's law, and the polarizing angle** θ_p **is sometimes** called **Brewster's angle**

Malus’s Law

Malus’s Law

- When polarized light of intensity $I_{\max}$ is emitted by a polarizer and then incident on an analyzer, the intensity of the (polarized) beam transmitted through the analyzer varies as

$$\boxed{I = I_{\max} \cos^2 \theta}$$

where $I_{\max}$ is the intensity of the polarized beam incident on the analyzer.

This expression, known as **Malus’s law**, applies to any two polarizing materials whose transmission axes are at an angle θ to each other.

- The intensity of the transmitted beam is maximum when the transmission axes are parallel $\left(\theta = 0 \text{ or } 180^0\right)$ and that it is zero when the transmission axes are perpendicular to each other.

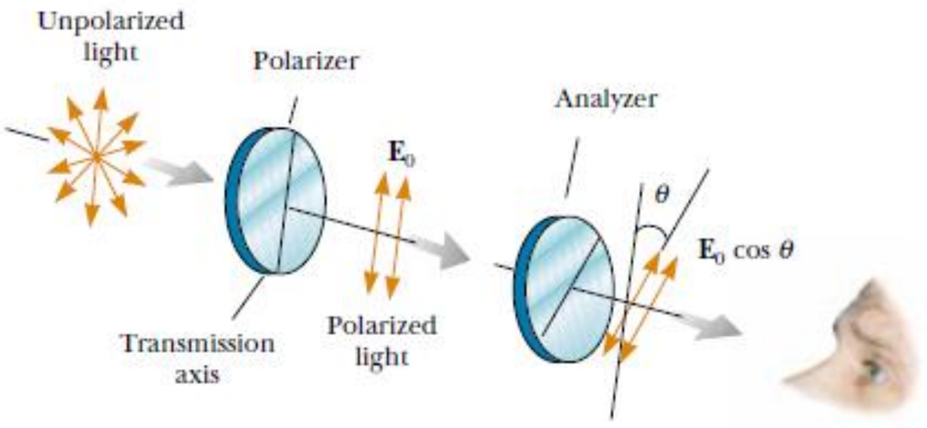


Figure M-1

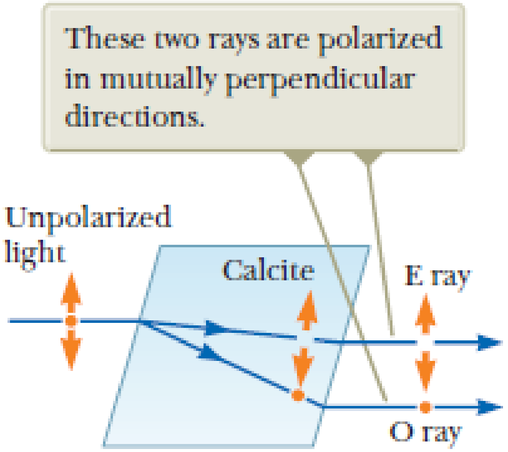
Two polarizing sheets whose transmission axes make an angle θ with each other. Only a fraction of the polarized light incident on the analyzer is transmitted through it.

POLARIZATION

Polarization by Double Refraction

Polarization by Double Refraction

- Solids can be classified on the basis of internal structure. Those in which the atoms are arranged in a specific order are called *crystalline*. Those solids in which the atoms are distributed randomly are called *amorphous*.
- When light travels through an amorphous material, such as glass, it travels with a speed that is the same in all directions. That is, glass has a single index of refraction.
- In certain crystalline materials such as calcite and quartz, however, the speed of light is not the same in all directions. Such materials are characterized by two indices of refraction. Hence, they are often referred to as **double-refracting** or **birefringent** materials.
- When unpolarized light enters a **birefringent** material, it may split into an **ordinary (O) ray** and an **extraordinary (E) ray**. These two rays have mutually perpendicular polarizations and travel at different speeds through the material. The two speeds correspond to two indices of refraction, μ_O for the ordinary ray and μ_E for extraordinary ray.
-



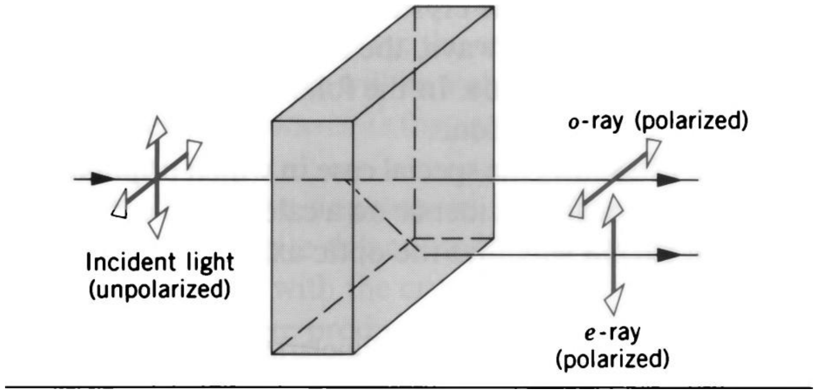


Figure DR-1

Unpolarized light incident on a birefringent material (a calcite crystal) splits into an ordinary (O) ray and an extraordinary (E) ray (which does not follow Snell's law). These two rays are polarized in mutually perpendicular directions.

Polarization by Double Refraction

Polarization by Double Refraction

- Solids can be classified on the basis of internal structure. Those in which the atoms are arranged in a specific order are called *crystalline*. Those solids in which the atoms are distributed randomly are called *amorphous*.
- When light travels through an amorphous material, such as glass, it travels with a speed that is the same in all directions. That is, glass has a single index of refraction.
- In certain crystalline materials such as calcite and quartz, however, the speed of light is not the same in all directions. Such materials are characterized by two indices of refraction. Hence, they are often referred to as **double-refracting** or **birefringent** materials.
- When unpolarized light enters a **birefringent** material, it may split into an **ordinary (O) ray** and an **extraordinary (E) ray**. These two rays have mutually perpendicular polarizations and travel at different speeds through the material. The two speeds correspond to two indices of refraction, μ_O for the ordinary ray and μ_E for extraordinary ray.
-

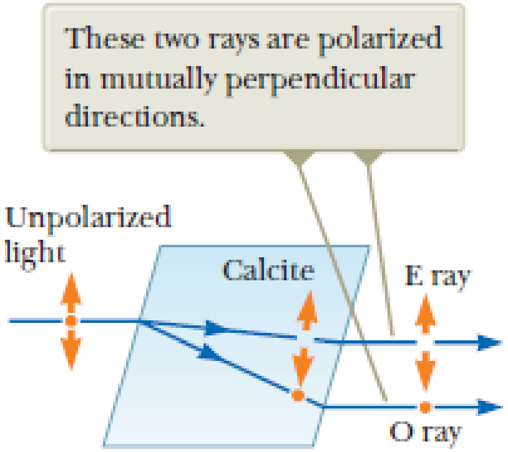


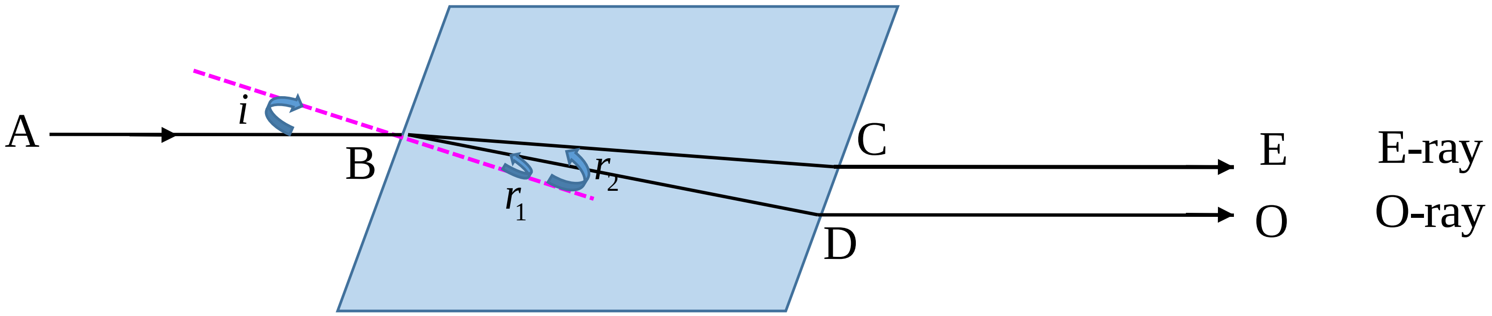
Figure DR-1
Unpolarized light incident on a calcite crystal splits into an ordinary (O) ray and an extraordinary (E) ray.
These two rays are polarized in mutually perpendicular directions.

Double Refraction

Double Refraction

- In 1669, Erasmus Bartholinus discovered that when an unpolarized beam of light enters an birefringent material like crystal or quartz, it splits into two plane polarized refracted beams travelling in different directions, one of which [O-ray] always obeys ordinary laws of refraction and the other [E-ray], in general, does not obey them. This phenomenon is known as ***double refraction***.

- Let a ray AB be incident on a calcite crystal at an angle of incidence ‘ i’. The ray AB is split up inside the crystal into two refracted rays along BC and BD such that angles of refractions are r_1 and r_2 respectively. The rays emerge from the crystal along CE and DO which are parallel.



- The refractive index of ordinary ray, $\mu_o = \frac{\sin i}{\sin r_1}$ and that of extraordinary ray, $\mu_e = \frac{\sin i}{\sin r_2}$. It is observed that index of ordinary ray is constant while refractive index of extraordinary ray varies with the angle of incidence ‘ i’.

- In calcite crystal, $r_1 < r_2$ therefore, $\mu_o > \mu_e$. Hence the velocity of ordinary ray is less than that of velocity of extraordinary ray $(v_o < v_e)$. Such crystals are called ***negative crystals*** for examples tourmaline and ruby.

- Positive Crystals - quartz, iron oxide: $\mu_e > \mu_o$

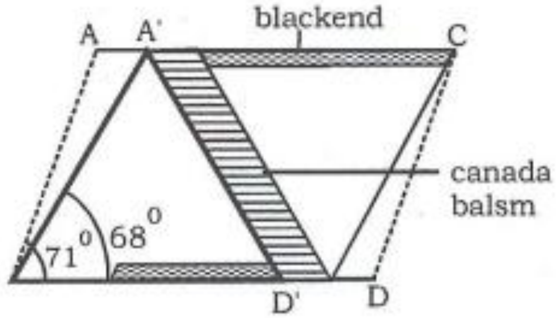
Nicol Prism

Nicol Prism

- In 1828, William Nicol designed an ingenious optical device by specially cutting calcite crystal for producing and analyzing plane polarized light. It is known as the ***Nicol Prism.***
- Its principle is based on the phenomenon of double refraction.
- Actually, the Nicol prism is not a prism but a parallelepiped.
- It is well known that when an unpolarized beam enters the calcite crystal, it splits up into two plane polarized rays, as O-rays and E-rays, with vibrations in two mutually perpendicular planes. If by some optical means, we eliminate one of the beams, then we would obtain only one plane polarized beam. The Nicol prism is designed in such a way so as to eliminate the ordinary ray by total internal reflection. Hence only the E-ray is transmitted through the prism.
- **Construction**

A calcite crystal of length 3 times its breadth is cut along the proper direction. Its principal section is a parallelogram of 71° and 109° angles. The two pieces are ground so that the angles of principal section are changed to 68° and 112°as shown in the Figure N-1.

The two pieces are joined together along diagonal AD by sticky liquid known as Canada balsam. The side faces are blackened.



Nicol Prism as Polarizer and Analyzer

Nicol Prism as Polarizer and Analyzer

- It is an optical device made up of calcite crystal and used for producing and analyzing plane polarized light.
- We know that when ordinary light is passed through calcite crystal, it splits up in to two rays; one is ordinary ray (O-ray) and the other is extraordinary ray (E-ray). The Nicol prism is made in such a way that it eliminates one of the two rays by total internal reflection. It is found that the ordinary ray is eliminated and only the extraordinary ray is transmitted through the prism.
- A calcite crystal is suitably cut in to two pieces and then cemented optically by a transparent material called Canada Balsam, whose refractive index lies between the refractive indices for ordinary and extraordinary rays for calcite.
- The numerical values of refractive indices are

  Refractive index of calcite for ordinary ray, $\mu_o = 1.66$

  Refractive index of Canada Balsam, $\mu = 1.55$

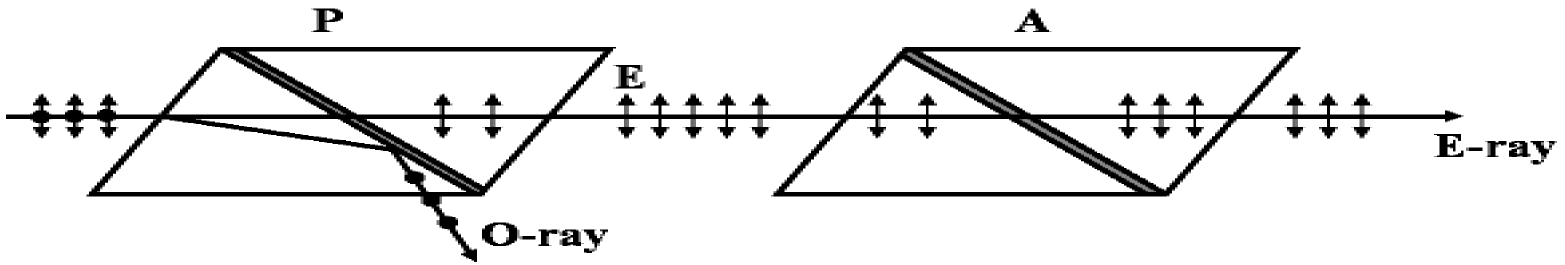
  Refractive index of calcite for extraordinary ray, $\mu_e = 1.49$

- Thus, we see that Canada Balsam is optically denser than calcite for E-ray and rarer for O-ray. So, O-ray is totally internally reflected and only E-ray is transmitted through the prism, which is plane polarized light. Hence Nicol prism acts as polarizer.

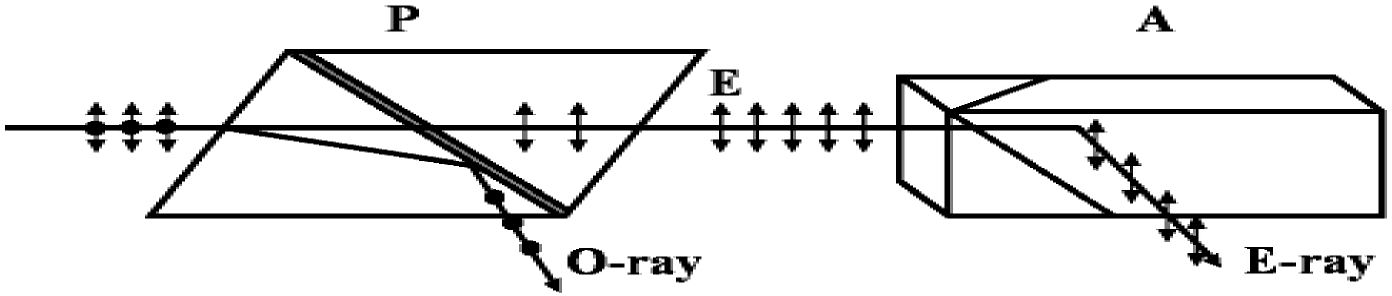
Nicol Prism as Polarizer and Analyzer

Nicol Prism as Polarizer and Analyzer

- Now to analyze the polarized ray, second Nicol prism is placed adjacent to first as shown in figure below.



- Here Nicol prism P acts as polarizer and Nicol prism A acts as analyzer. The planes of both Nicol prisms are parallel, so according to Malus law intensity of polarized ray transmitted from analyzer is maximum.



- Now Nicol prism A is gradually rotated, the intensity of final transmitted E-ray decreases in accordance with Malus law and when planes of these Nicol prisms are crossed (perpendicular to each other), the intensity of light transmitted from analyzer is zero i.e. E-ray is totally internally reflected by analyzer.

Thus, Nicol prism can be used both as polarizer and analyzer.

Optical Activity

Optical Activity

- The ability of certain substances to rotate the plane of polarization of plane-polarized light as it passes through them.

- **Optically Active Substance** rotates the plane of polarization of plane-polarized light transmitted through the substance.

  Example: Sugar solution

- Dextrorotatory:

  Optical active substance that rotates plane of polarization towards the right i.e. in clockwise direction on looking towards the source.

- Laevorotatory:

  Optical active substance that rotates plane of polarization towards the left i.e. in anti-clockwise direction on looking towards the source.

Specific Rotation

Specific Rotation

- The angle through which the plane of polarization is rotated depends upon:

    i. thickness of the substance,

    ii. concentration of the solution,

    iii. wavelength of light, and

    iv. the temperature.

- **Specific rotation** for a given wavelength of light at a given temperature is defined as the rotation produced by one decimeter length of the solution containing 1 g of optically active material per cc of solution.
- If is the rotation produced by L decimeters length of a solution and C the concentration in grams per cc, the specific rotation S at a given temperature T, corresponding to a wavelength λ is given by

$$[S]_{\lambda}^{T} = \frac{\theta}{L \times C} = \frac{\text{Rotation in degrees}}{\text{Length in decimetre} \times \text{Concentration in } {}^{g}\!/_{cm^3}}$$

- SI unit of specific rotation is degree dm^{-1} g^{-1} cm^{3}.

POLARIZATION

References

1. **R.A. Serway and J.W. Jewett**, Physics for Scientist and Engineers with Modern Physics

2. **Halliday and Resnick**, Fundamental of Physics

3. **D. Halliday, R. Resnick, and K. Krane** , Physics, Volume II, Fourth Edition

4. **Hugh D. Young, Roger A. Freedman,** University Physics with Modern Physics, 13TH Edition

Thank you