Birefringence

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The phenomenon of birefringence comes about due to the phenomenon of double refraction. Double refraction occurs due to the fact that some molecules have an inherent axis due to their structure. These crystals do not ‘look’ the same, from a physical point of view, in all directions and are also called “anisotropic” crystals. As light propagates inside such a material, the electrons are driven into oscillations preferentially in the direction of this axis – called the ‘optic axis’. This preference for the electrons to be driven in a specific direction results in two waves being propagated in the crystal at different speeds – one parallel to the direction of the axis and one perpendicular to it, so a beam of light entering a birefringent material is split into two mutually perpendicularly polarized beams, propagating in two different directions at two different speeds. Also, the two beams are polarized perpendicular to each other, so if an unpolarised beam entered a birefringent crystal, the beam would split into a polarization parallel to the optic axis and one perpendicular to the optic axis. The beam whose polarization is perpendicular to the optic axis would propagate inside the crystal as if the beam were entering a piece of glass, ie it would propagate spherically and would refract according to Snell’s Law, such a beam is known as the o wave (‘o’ for ‘ordinary’). Meanwhile the beam whose polarization is parallel to the optic axis would propagate as an ellipse and would travel at right angles to the optic axis and is known as the ‘e’ wave. Sometimes these waves are called the ‘fast’ and ‘slow’ beams due to the different speeds of propagation. Which one is the ‘slow’ and which the ‘fast’ depends on whether the crystal is a positive one (‘o’ faster than ‘e’) or a negative one (‘e’ faster than ‘o’). Sometimes the optic axis is referred to as the ‘fast’ axis, for a negative crystal whose e wave is faster than the o wave, or a ‘slow’ axis, for a positive crystal when the o wave is the faster one (see Fig 1)

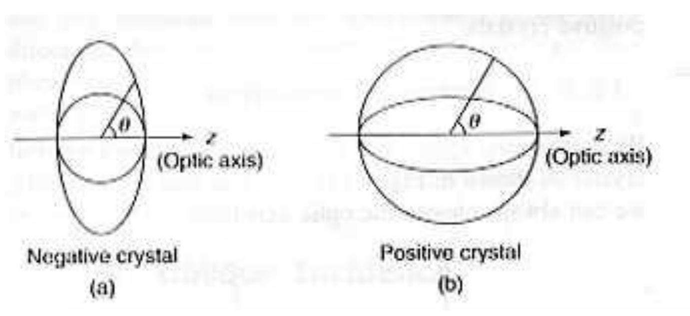

Fig 1 The optic axis is along the z axis. The e wave propagates as an ellipsoid, while the o wave propagates spherically. In a negative crystal, the e wave is faster and the axis is a fast axis. In a positive crystal the o wave is faster.

Light Entering a birefringent crystal at normal incidence

If light entered at normal incidence into a birefringent crystal whose optic axis is parallel to either face of the crystal, then both the e wave and the o wave propagate in the same direction. However the speed with which they travel through the crystal depends on the exact orientation of the optic axis in relation to the incoming beam

If the optic axis was perpendicular to the beam direction and in the plane of incidence (Fig 2), then light polarized perpendicular to the optic axis (shown as dots in the figure) would be the 'o' wave and would propagate spherically, while the light polarized parallel to the optic axis (shown as lines across the beam path in the figure) would be the 'e' wave and would travel elliptically and so faster than the o wave. Since the e wave is travelling faster than the o wave (in a negative crystal), there would be a phase mismatch at the face where the beams exited. This phase mismatch is exploited in creating a half- or quarter-wave plate.

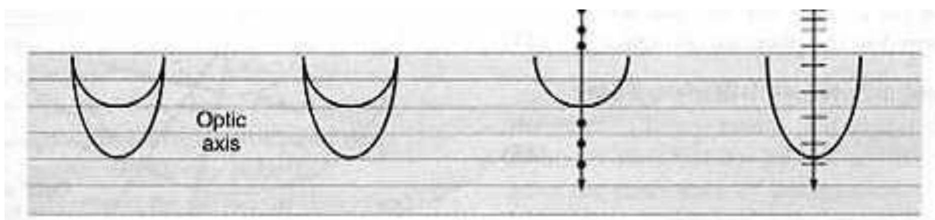

Fig 2 The optic axis is perpendicular to the beam direction. The o wave is polarized perpendicular to the optic axis, while the (faster) e wave propagates elliptically and is polarized parallel to the optic axis

If the optic axis were parallel to the beam direction (Fig 3), then both the e wave and the o wave travel at the same speed in the forward direction. However, once more, the e wave is p polarized and the o wave is s polarized.

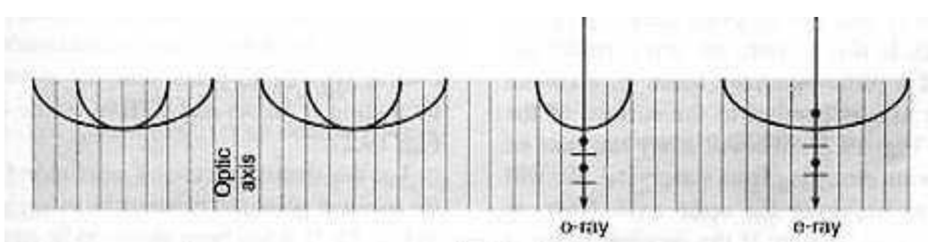

Fig 3 The optic axis is parallel to the beam direction. Both beams travel at the same speed but are perpendicularly polarized.

Optic axis at an angle to the incoming, normally incident beam

If the beam entered the crystal at normal incidence, but the optic axis were at an angle to the beam direction and the crystal faces, then two distinct beams will result (Fig 4). The o wave would act just as a wave entering a non-birefringent crystal and would propagate normally through the crystal as divergent spherical waves. However, the velocity of the e wave depends on the angle it makes with the optic axis. The beam achieves its greatest speed normal to the optic axis, while along the optic axis, it's speed is the same as the o wave. This deforms the e wave into an elliptical shape as it traverses the crystal. In addition, due to the twist in the optic axis with respect to the face of the crystal, the e wave changes direction and a new wave is created. Thus two waves exit the crystal at the far face, the o and the e waves.

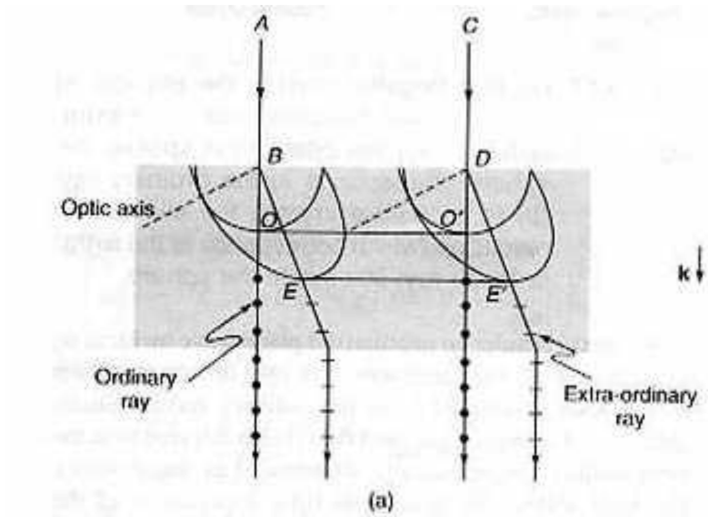

Fig 4 The beam enters at normal incidence to the crystal face. The optic axis (dotted line) is at an angle to the crystal face, hence the light is split into two beams parallel and perpendicular to the optic axis. Once again, the o wave is s polarised and the e wave is p polarised.

It can be shown that if the beam entered the crystal at an oblique angle of incidence, there would be a separation of o wave and e wave. The o wave would propagate in a direction given by Snell's Law, while the e beam's direction would be dependant on the angle the beam made with the optic axis. Light perpendicular to the optic axis would travel faster than light parallel to the optic axis and the beam would propagate elliptically. Again, the o wave is s polarized and the e wave is p polarized.