

It is to be noted that the hand may be soon trained to detect a difference of specific gravity, if like volumes are taken, even in a small fragment — thus the difference between calcite or albite and barite, even the difference between a small diamond and a quartz crystal, can be detected.

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## III. CHARACTERS DEPENDING UPON LIGHT

## GENERAL PRINCIPLES OF OPTICS

**306.** Before considering the optical characters of minerals in general, and more particularly those that belong to the crystals of the different systems, it is desirable to review briefly some of the more important principles of optics upon which the phenomena in question depend.

For a fuller discussion of the optics of crystals, special reference is made to the works of Groth (translation by Jackson), Liebisch, Mallard, Duparc and Pearce, Rosenbusch (translation by Iddings), Iddings, Johannsen, Winchell, mentioned on p. 3 also to the various advanced text-books of Physics.

**307. The Nature of Light.** — Light is now considered to be an electromagnetic phenomenon due to a periodic variation in the energy given off by vibrating electrons. This energy is transmitted by a series of periodic changes that show all the characters of ordinary wave phenomena. The light waves, as they are commonly called, possess certain short wave-lengths that are of the correct magnitude to affect the optic nerves. Other similar waves with longer or shorter wave-lengths belong to the same class of phenomena. Immediately beyond the violet end of the visible spectrum come the so-called "ultra-violet" waves with still shorter wave-lengths and on beyond these we have the X-rays and the "gamma" rays produced by radium. Of the waves having greater lengths than those of light waves we have the waves that give

rise to the sensation of heat and the Hertzian waves used in wireless. All of these vibrations, while varying enormously in their wave-lengths, belong to the same order of phenomena and obey the same laws. The proportion that the section of the series which produces the effect of light bears to the whole may be strikingly shown when we say that if ordinary white light is broken up into a spectrum a yard long and this then considered to be extended on either end so as to include all known electro-magnetic waves the entire spectrum would be over five million miles in length.

The transmission of light through interstellar space, through liquids and transparent solids, has for some time been explained by the assumption that a medium, called the luminiferous ether, pervades all space, including the intermolecular space of material bodies. In this medium the vibrations of light waves are assumed to take place. For the purposes of the present work, however, it is unnecessary to consider closely the exact nature of light or the mode of its transmission. It will assist greatly, however, in obtaining a clear idea of the behavior of light in crystals if we assume that light waves are mechanical in nature and consist of periodic vibrations in an all-prevailing ether.

**308. Wave-motion in General.** — A familiar example of wave-motion is given by the series of concentric waves which on a surface of smooth water go out from a center of disturbance, as the point where a pebble has been dropped in. These surface-waves are propagated by a motion of the water-particles which is *transverse* to the direction in which the waves themselves travel; this motion is given from each particle to the next adjoining, and so on. Thus the particles of water at any one spot oscillate up and down,\* while the wave moves on as a circular ridge of water of constantly increasing diameter, but of diminishing height. The ridge is followed by a valley, indeed both together properly constitute a wave in the physical sense. This compound wave is followed by another wave and another, until the original impulse has exhausted itself.

Another familiar kind of wave-motion is illustrated by the sound-waves which in the free air travel outward from a sonorous body in the form of concentric spheres. Here the actual motion of the layers of air is forward and back — that is, in the direction of propagation of the sound — and the effect of the transfer of this impulse from one layer to the next is to give rise alternately to a condensed and rarefied shell of air, which together constitute a sound-wave and which expand in spherical waves of constantly decreasing intensity (since the mass of air set in motion continually increases). Sound-waves, as of the voice, may be several feet in length, and they travel at a rate of 1120 feet per second at ordinary temperatures.

**309.** It is important to understand that in both the cases mentioned, as in every case of free wave-motion, each point on a given wave may be considered as a center of disturbance from which a system of new waves tend to go out. These individual wave-systems ordinarily destroy each other except so far as the onward progression of the wave as a whole is concerned. This is further discussed and illustrated in its application to light-waves (Art 312 and Figs. 509, 510).

In general, therefore, a given wave is to be considered as the resultant of all these minor wave-systems. If, however, a wave encounters an obstacle in its path, as a narrow opening (*i.e.*, one narrow in comparison with the length

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\* Strictly speaking, the path of each particle approximates closely to a circle.

of the wave) or a sharp edge, then the fact just mentioned explains how the waves seem to bend about the obstacles, since new waves start from them as centers. This principle has an important application in the case of light-waves, explaining the phenomena of diffraction (Art. 331).

**310.** Still another case of wave-motion may be mentioned, since it is particularly helpful in giving a correct apprehension of light-phenomena. If a long rope, attached at one end, be grasped at the other, a quick motion of the hand, up or down, will give rise to a half wave-form — in one case a crest, in the other a trough — which will travel quickly to the other end and be reflected back with a reversal in its position; that is, if it went forward as a hill-like wave, it will return as a trough. If, just as the wave has reached the end, a second like one be started, the two will meet and pass in the middle, but here for a brief interval the rope is sensibly at rest, since it feels two equal and opposite impulses. This will be seen later to be a case of the simple interference of two like waves opposed in phase.

Again, a double motion of the hand, up and down, will produce a complete wave, with crest and trough, as the result, and this again is reflected back as in the simpler case. Still again, if a series of like motions are continued rhythmically and so timed that each wave is an even part of the whole rope, the two systems of equal and opposite waves passing in the two directions will interfere and a system of so-called stationary waves will be the result, the rope seeming to vibrate in segments to and fro about the position of equilibrium.

Finally, if the end of the rope be made to describe a small circle at a rapid, uniform, rhythmical rate, a system of stationary waves will again result, but now the vibrations of the string will be sensibly in circles about the central line. This last case will be seen to roughly indicate the kind of transverse vibrations by which the waves of circularly polarized light are propagated, while the former case represents the vibrations of waves of what is called plane-polarized light.

All these cases of waves obtained with a rope deserve to be carefully considered and studied by experiment, for the sake of the assistance they give to an understanding of the complex phenomena of light-waves.

**311. Light-waves.** — In the discussion that follows, in order to make the explanations simpler and clearer, light waves have been treated as if they consisted of mechanical disturbances in a material medium called the ether.

The vibrations in the ether caused by the transmission of a light wave take place in directions transverse to the direction of the movement of the wave. These oscillations have the following characters. When an ether particle is set vibrating it moves from its original position with gradually decreasing velocity until the position of its maximum displacement is reached. Then with gradually increasing velocity it returns to its original position and since it is moving without friction it will continue in the same direction on past this point. Its velocity will then again diminish until it has reached a displacement equal but opposite in direction to its first swing, when it will start back on its course and repeat the oscillation. The varying velocity of such an oscillation would be the same as that shown by a particle moving around a circle with uniform speed if the particle was observed in a direction lying in the plane of the circle. Under these conditions the particle would appear to move forward and backward along a straight line with constantly changing velocity. Such a motion is called simple harmonic motion.

The motion of one ether particle is communicated to another and so on, each, in order, falling a little behind in the time of its oscillation. Consequently, while the individual particles move only back and forth in the same line the wave disturbance moves forward. If, at a given instant of time, the positions of successive particles in their oscillations are plotted, a curve, such as shown in Fig. 508, will be formed. Such a curve is known as a harmonic curve. The oscillatory motion of the particles in a light wave is called a *periodic motion* since it repeats itself at regular intervals. The maximum dis-

placement of a particle from its original position of rest is called the *amplitude* of the wave (distance C-D, Fig. 508). The *phase* of a particle at a given instant is its position in the vibration and the direction in which it is moving.

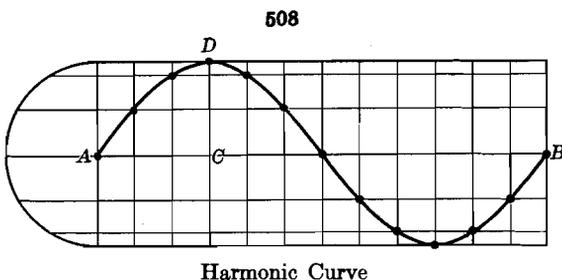
The distance between any particle and the next which is in a like position — *i.e.*, of like *phase*, as A and B — is the *wave-length*; and the time required for this completed movement is the *time* of vibration, or *vibration-period*.

The wave-system therefore travels onward the distance of one wave-length in one vibration-period. The intensity of the light varies with the amplitude of the vibration, and the color, as explained in a later article, depends upon the length of the waves; the length of the violet waves is about one-half the length of the red waves.

In *ordinary light* the transverse vibrations are to be thought of as taking place in all planes about the line of propagation. In the above figure, vibrations in one plane only are represented; light that has only one direction of transverse vibration is said to be *plane-polarized*.

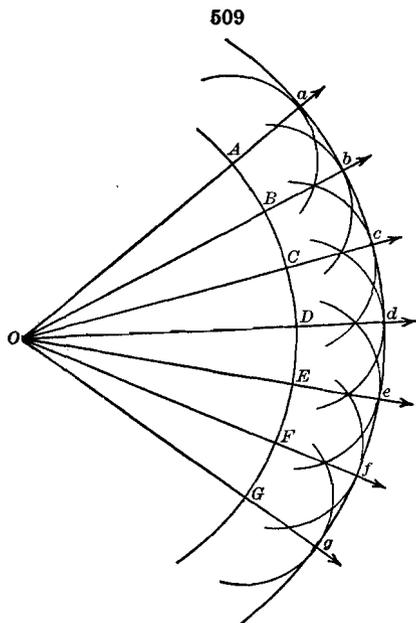
Light-waves have a very minute length, only 0'000023 of an inch for the yellow sodium flame, and they travel with enormous velocity, 186,000 miles per second in a vacuum; thus light passes from the sun to the earth in about eight minutes. The vibration-period, or time of one oscillation, is consequently extremely brief; it is given by dividing the distance traveled by light in one second by the number of waves included.\*

**312. Wave-front.** — In an isotropic medium, as air, water, or glass — that is, one in which light would be propagated in all directions about a luminous point with the same velocity — the waves are spherical in form. The *wave-front* is the continuous surface, in this case spherical, which includes all particles that commence their vibration at the same moment of time. Obviously the curvature of the wave-front diminishes as the distance of the source of light increases, and when the light comes from an indefinitely great distance (as the sun) the wave-front becomes sensibly a plane surface. Such waves are usually called *plane waves*. These cases are illustrated by Figs. 509 and 510. In Fig. 509 the luminous point is supposed to be O, and the medium being isotropic, it is obvious that the wave-front, as ABC . . . G, is spherical. It is also made clear by this figure how, as briefly stated in Art. 309, the resultant of all the individual impulses which go out from the successive points, as A, B, C, etc., as centers, form a new wave-front, abc . . . g, concentric with ABC . . . G. In Fig. 510 the luminous body is supposed to be at a great dis-

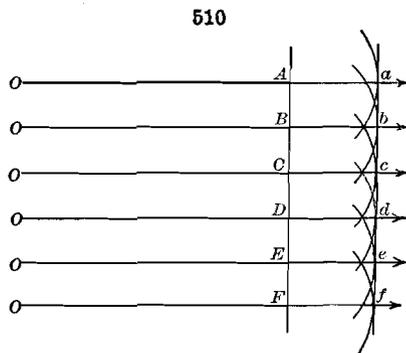


\* "On account of the tremendous speed at which light travels the rapidity of vibration, or "frequency" of light as it passes through a fixed point, is extremely great. About eight hundred trillion waves of violet light would pass through such a point in a second. The extreme brevity of the interval of time required for the passage of a single wave of this sort may perhaps be realized better when it is said that one eight-hundred-trillionth of a second is a vastly smaller part of a second than a second is of the whole of historic time." Comstock and Troland, "The Nature of Matter and Electricity," p. 157.

tance, so that the wave-front  $AB \dots F$  is a plane surface. Here also the individual impulses from  $A, B$ , etc., unite to form the wave-front  $ab \dots f$  parallel to  $AB \dots F$ .



**313. Light-ray.** — The study of light-phenomena is, in certain cases, facilitated by the conception of a *light-ray*, a line drawn from the luminous point to the wave-front, and whose direction is taken so as to represent that of the wave itself.



In Fig. 509  $OA, OB$ , etc., are diverging light-rays, and in Fig. 510  $OA, OB$ , etc., are parallel light-rays. In both these cases, where the medium is assumed to be isotropic, the light-ray is normal to the wave-front. This is equivalent to saying that the light-wave moves onward in a direction normal to the wave-front.

It must be understood that the “light-ray” has no real existence and is to be taken only as a convenient method of representing the direction of motion of the light-waves under varying conditions. Thus when by appropriate means (*e.g.*, the use of lenses) the curvature of the wave-front is altered — for example, if from being a plane surface it is made sharply convex — then the light-rays, at first parallel, are said to be made to diverge. Again, if the convex wave-front is made plane, the diverging light-rays are then said to be made parallel.

**314. Wave-length. Color. White Light.** — Notwithstanding the very small length of the waves of light, they can be measured with great precision. The visual part of the waves going out from a brilliantly incandescent body, as the glowing carbons of an electric arc-light, may be shown to consist of waves of widely varying lengths. They include red waves whose length is 0.0007604 mm. (about  $\frac{1}{39,000}$  of an inch) and waves whose length constantly diminishes without break, through the orange, yellow, green, and blue to the violet, whose minimum length (0.0003968 mm.) is about half of that of the red. The color of light is commonly said to depend upon its wave-length and will be so spoken of here. This is not strictly true, however, because, since the velocity of light varies with the medium through which it is traveling

while the vibration period remains constant under all conditions, it follows that the wave-length of light of the same color must be different in different media. It is, therefore, rather the frequency with which the light waves reach the eye that determines the color sensation. Commonly a given color is produced by the combination of several different wave-lengths of light. It is strictly *monochromatic* only when it corresponds to one definite wave-length; this is nearly true of the bright-yellow sodium line, though strictly speaking this consists of two sets of waves of slightly different lengths.

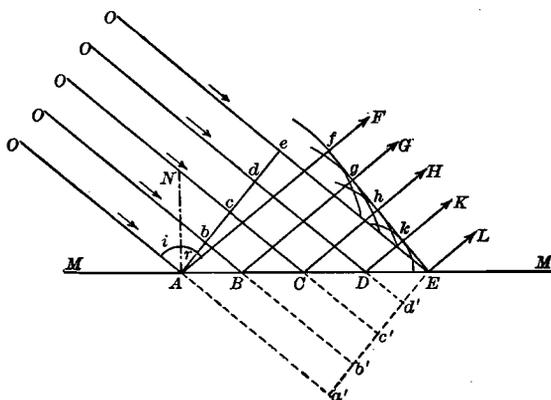
The effect of "white light" is obtained if all the waves from the red to the violet come together to the eye simultaneously; for this reason a piece of platinum at a temperature of 1500° C. appears "white hot."

The radiation from the sources named, either the sun, the electric carbons, or the glowing platinum, includes also longer waves which do not affect the eye, but which, like the light-waves, produce the effect of sensible heat when received upon an absorbing surface, as one of lamp-black. There are also, particularly in the radiation from the sun, waves shorter than the violet which also do not affect the eye. The former are called *infra-red*, the latter *ultra-violet* waves.

511

The *brightness* of light depends upon the amplitude of its vibrations and varies directly as the square of this distance.

**315. Complementary Colors.** — The sensation of white light mentioned above is also obtained when to a given color — that is, light-waves of given wave-length — is combined a certain other so-called *complementary* color. Thus certain shades

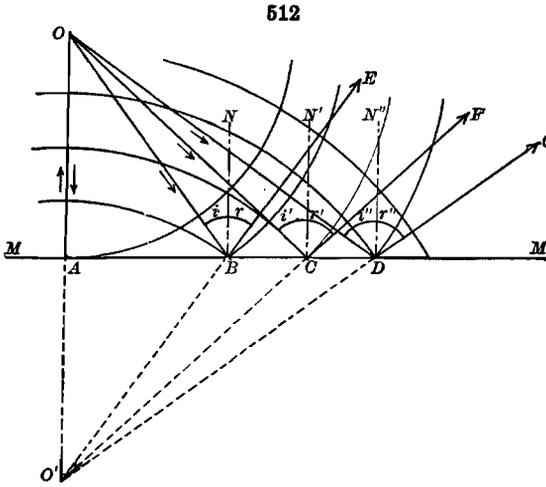


of pink and green combined, as by the rapid rotation of a card on which the colors form segments, produce the effect of white. Blue and yellow of certain shades are also complementary. For every shade of color in the spectrum there is another one complementary to it in the sense here defined. The most perfect illustration of complementary colors is given by the examination of sections of crystals in polarized light, as later explained.

**316. Reflection.** — When light-waves come to the boundary which separates one medium from another, as a surface of water, or glass in air, they are, in general, in part *reflected* or returned back into the first medium.

The reflection of light-waves is illustrated by Figs. 511 and 512. In Fig. 511, *MM* is the reflecting surface — here a plane surface — and the light-waves have a plane wave-front (*Abcde*); in other words, the light-rays (*OA, Ob*, etc.) are parallel. It is obvious that the wave-front meets the surface first at *A* and successively from point to point to *E*. These points are to be regarded as the centers of new wave-systems which unimpeded would be propagated outward in all directions and at a given instant would have traveled through distances equal to the lines *Aa', Bb'*, etc. Hence the com-

mon tangent  $fghkE$  to the circular arcs drawn with these radii from  $A, B,$  etc., represents the direction of the new or reflected wave-front. But geomet-



rically the angle  $eAE$  is equal to  $fEA$ , or the *incident and reflected wave-fronts make equal angles with the reflecting surface*. If  $NA$  is a normal at  $A$ , the angle  $OAN$  — called the *angle of incidence* — is equal to  $NAF$ , the *angle of reflection*. Hence the familiar law:

*The angle of incidence is equal to the angle of reflection.*

Furthermore, the “incident and reflected rays” both lie in the same plane with the normal to the reflecting surface.

In Fig. 512, where the luminous point is at  $O$ , the waves going out from it will meet the plane mirror  $MM$  first at the point  $A$  and successively at points, as  $B, C, D,$  etc., farther away to the right (and left) of  $A$ . Here also it is easy to show that all the new impulses, which have their centers at  $A, B, C,$  etc., must together give rise to a series of reflected waves whose center is at  $O'$ , at a distance equally great from  $MM$  measured on a normal to the surface ( $OA = O'A$ ).

Now the lines  $OA, OB,$  etc., which are perpendicular to the wave-front, represent certain incident light-rays, and the eye placed in the direction  $BE, CF,$  etc., will see the luminous point as if at  $O'$ . It follows from the construction of the figure and can be proved by experiment that if  $BN, CN',$  etc., are normals to the mirror the angles of incidence,  $OBN, OCN',$  etc., are equal to the angles of reflection,  $NBE, N'CF,$  etc., respectively. Hence the above law applies to this case also.

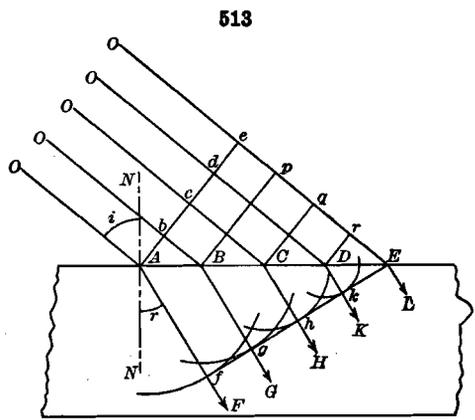
If the reflecting surface is not plane, but, for example, a concave surface, as that of a spherical or parabolic mirror, there is a change in the curvature of the wave-front after reflection, but the same law still holds true.

The proportion of the reflected to the incident light increases with the smoothness of the surface and also as the angle of incidence diminishes. The intensity of the reflected light is a maximum for a given surface in the case of perpendicular incidence ( $OA$ , Fig. 512).

If the surface is not perfectly polished, *diffuse reflection* will take place, and there will be no distinct reflected ray. It is the diffusely reflected light which makes the reflected surface visible; if the surface of a mirror were *absolutely smooth* the eye would see the reflected body in it only, not the surface itself. Optically expressed, the surface is to be considered smooth if the distance between the scratches upon it is considerably less (say one-fourth) than the wave-length of light.

**317. Refraction.** — When light passes from one medium into another there is, in general, an increase or decrease in its velocity, and this commonly results in the phenomenon of *refraction* — that is, a change in the direction of propagation. The principles applicable here can be most easily shown in the

case of light-waves with a plane wave-front, as shown in Fig. 513 — that is, where the light-rays  $OA, OB$ , etc., are parallel. Suppose, for example, that a light-wave, part of whose wave-front is  $abcde$ , passes from air obliquely into glass, in which its velocity is about two-thirds as great as it was in the air and suppose the surface of the glass to be plane. At the moment that the ray  $O-A$  enters the glass the ray  $O-E$  has reached the point  $e$ . During the time that the latter ray travels from  $e$  to  $E$ , the ray  $O-A$  will have advanced in the glass a distance equal to  $\frac{2}{3}e-E$ , or to some point on an arc having this distance as a radius ( $A-f$ ). In the same way during the time ray  $O-E$  passes from the point  $p$  to  $E$ , ray  $O-B$  will have traveled in the glass the distance  $B-g$ , equal to  $\frac{2}{3}p-E$ . In this way arcs may be drawn about each one of the points  $A, B, C$ , etc., and the position of the new wave-front in the glass determined by their common tangent,  $Ekhgf$ . It is seen that there is a change of direction in the wave-front, or otherwise stated, in the light-ray, the magnitude of which depends on the ratio between the light-velocities in the two media, and, as discussed later, also upon the wave-length of the light. The light-ray is here said to be broken or *refracted*, and for a medium like glass, optically denser than air (*i.e.*, with a lower value of the light-velocity), the refraction is toward the perpendicular with the angle of refraction,  $r$ , smaller than the angle of incidence,  $i$ . In the opposite case — when light passes into an optically rarer medium — the refraction is away from the perpendicular and the angle of refraction is larger than that of incidence (Art. 323).



**318. Refractive Index.** — It is obvious from the figure that whatever the direction of the wave-front — that is, of the light-rays — relatively to the given surface, the *ratio* of  $eE$  to  $Af$ , which determines the direction of the new wave-front (*i.e.*, the direction of a refracted ray,  $AF$ ) is constant. This ratio is equal to  $\frac{V}{v}$  where  $V$  is the value of the light-velocity for the first medium (here air) and  $v$  for the second (as glass). This constant ratio is commonly represented by  $n$  and is known as the *index of refraction*. Therefore

$$n = \frac{eE}{Af}$$

In Fig. 513, by construction,

$$\angle eAE = \angle i \quad \text{and} \quad \angle AEf = \angle r.$$

Also,

$$\frac{eE}{AE} = \sin i \quad \text{and} \quad \frac{Af}{AE} = \sin r.$$

Therefore,

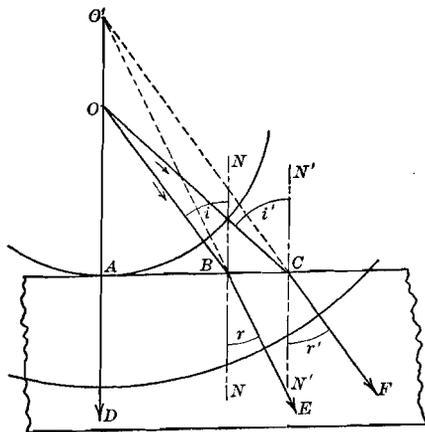
$$\frac{\sin i}{\sin r} = \frac{\frac{eE}{AE}}{\frac{Af}{AE}} = \frac{eE}{Af} = n.$$

The law of refraction then is given by the expression,  $n = \frac{\sin i}{\sin r}$ , or may be formulated as follows:

*The sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction.*

In the case of light passing from air into crown glass this ratio is found to be,  $\frac{\sin i}{\sin r} = 1.608$ , and this number consequently gives the value of the refractive index, or  $n$ , for this kind of glass.

514



The above relation holds true for any wave-system of given wave-length in passing from one medium into another, whatever the wave-front or shape of the bounding surface. In Fig. 514 the luminous point is at  $O$ , and it can be readily shown that the new wave-front propagated in the second medium (of greater optical density) has a flattened curvature and corresponding to this a center at  $O'$  (where  $\frac{O'A}{OA} = \frac{V}{v}$ ). Here the incident rays  $OB, OC$ , are refracted at  $B$  and  $C$ , the corresponding refracted rays being  $BE$  and  $CF$ . For this case also the relation holds good,

$$n = \frac{\sin i}{\sin r} = \frac{\sin i'}{\sin r'}, \text{ etc.}$$

If the bounding surface is not plane but curved, as in lenses, there is a change in the curvature of the wave-front in the second medium, but the simple law,  $n = \frac{\sin i}{\sin r}$ , holds true here also, so long as the medium is isotropic.

The relation between wave-length and refractive index is spoken of in Art. 328.

**319. Relation of Refractive Index to Light-velocity.** — The discussion of the preceding article shows that if  $n$  is the refractive index of a given substance for waves of a certain length, referred to air,  $V$  the velocity in air and  $v$  the velocity in the given medium, then

$$n = \frac{V}{v}.$$

For two media whose indices are  $n_1$  and  $n_2$  respectively, it consequently follows that

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}.$$

Therefore, *The indices of refraction of two given media for a certain wavelength are inversely proportional to their relative light-velocities.*

In other words, if the velocity of light in air is taken as equal to 1 and the velocity of the same light is found to be one half as great when passing through a given substance, the index of refraction, or *n*, of that substance when referred to air (*n* = 1.0) will be equal to 2.0.

**320. Principal Refractive Indices.** — The refractive index has, as stated, a constant value for every substance, referred, as is usual, to air (or it may be to a vacuum). In regard to solid media, it is evident from Art. 318 and will be further explained later that those which are *isotropic*, viz., amorphous substances and crystals of the isometric system, can have but a single value of this index. Crystals of the tetragonal and hexagonal systems have, as later explained, *two* principal refractive indices,  $\epsilon$  and  $\omega$ , corresponding to the velocities of light-propagation in certain definite directions in them. Further, all orthorhombic, monoclinic, and triclinic crystals have similarly *three* principal indices,  $\alpha$ ,  $\beta$ ,  $\gamma$ . In the latter cases of so-called anisotropic media, the mean refractive index is taken, namely, as the arithmetical mean  $\frac{\epsilon + 2\omega}{3}$  and  $\frac{\alpha + \beta + \gamma}{3}$ .

**321. Effect of Index of Refraction upon Luster, etc.** — The luster and general appearance of a transparent substance depend largely upon its refractive index. For instance the peculiar aspect of the mineral cryolite, by means of which it is usually possible to readily identify the substance, is due to its low index of refraction. If cryolite is pulverized and the powder poured into a test tube of water it will disappear and apparently go into solution. It is quite insoluble, however, but becomes invisible in the water because its index of refraction (about 1.34) is near that of water (1.335). The light will travel with practically the same velocity through the cryolite as through the water and consequently suffer little reflection or refraction at the surfaces between the two. On the other hand powdered glass with a higher index of refraction than that of water appears white under the same conditions because of the reflection of light from the surfaces of the particles.

Substances having an unusually high index of refraction have an appearance which it is hard to define, and which is generally spoken of as an *adamantine luster*. This kind of luster may be best comprehended by examining specimens of diamond (*n* = 2.419) or of cerussite (*n* = 1.98). They have a flash and quality, sometimes almost a metallic appearance, which is not possessed by minerals of a low refractive index. Compare, for example, specimens of cerussite and fluorite (*n* = 1.434). The usual index of refraction for minerals may be said to range not far from 1.55, and gives to minerals a luster which has been termed *vitreous*. Quartz, feldspar, and halite show good examples of vitreous luster.

Below is given a list of common minerals arranged according to their indices of refraction. For minerals other than those of the isometric system the average value (as defined in the preceding article) is given here.

Water.....	1.335	Muscovite.....	1.582
Fluorite.....	1.434	Beryl.....	1.582
Orthoclase.....	1.523	Calcite.....	1.601
Gypsum.....	1.524	Topaz.....	1.622
Quartz.....	1.547	Tremolite.....	1.622

Dolomite.....	1·626	Anglesite.....	1·884
Aragonite.....	1·633	Zircon.....	1·952
Apatite.....	1·633	Cerussite.....	1·986
Barite.....	1·640	Cassiterite.....	2·029
Diopside.....	1·685	Sulphur.....	2·077
Cyanite.....	1·723	Sphalerite.....	2·369
Epidote.....	1·750	Diamond.....	2·419
Corundum.....	1·765	Rutile.....	2·711
Almandite.....	1·810	Cuprite.....	2·849
Malachite.....	1·880	Cinnabar.....	2·969

**322. Relations between Chemical Composition, Density, and Refractive Index.** — That definite relations exist between the chemical composition of a substance, its specific gravity, and its index of refraction, has been conclusively shown in many cases. With the plagioclase feldspar group, for instance, the variation in composition which the different members show is accompanied by a direct variation in density and refractive index. Attempts have been made to express these relations in the form of mathematical statements. The two most satisfactory expressions are the one proposed by Gladstone and Dale,\*  $\frac{n-1}{d} = \text{constant}$ , and the one proposed independently by Lorentz † and Lorenz, ‡  $\frac{n^2-1}{n^2+2} \cdot \frac{1}{d} = \text{constant}$ . In these  $n$  is equal to the mean refractive index and  $d$  to the density. These were originally proposed for use with gases and solutions and for these bodies have been found to serve about equally well. When attempts are made, however, to apply them to crystalline solids the results are at the best only approximate. § This is probably because the formulas do not take into consideration the modifications that the crystal structure must introduce.

**323. Total Reflection. Critical Angle.** — In regard to the principle stated in Art. 318 and expressed by the equation  $n = \frac{\sin i}{\sin r}$ , two points are to be noted. First, if the angle  $i = 0^\circ$ , then  $\sin i = 0$ , and obviously also  $r = 0$ ; in other words, when the ray of light (as  $OA$ , Fig. 514) coincides with the perpendicular, no change of direction takes place, the ray proceeds onward ( $AD$ ) into the second medium without deviation, but with a change of velocity.

Again, if the angle  $i = 90^\circ$ , then  $\sin i = 1$ , and the equation above becomes  $n = \frac{1}{\sin r}$  or  $\sin r = \frac{1}{n}$ . As  $n$  has a fixed value for every substance, it is obvious that there will also be a corresponding value of the angle  $r$  for the case mentioned. From the above table it is seen that for water,  $\sin r = \frac{1}{1.335}$  and  $r = 48^\circ 31'$ ; for crown glass ( $n = 1.608$ ),  $\sin r = \frac{1}{1.608}$  and  $r = 38^\circ 27'$ ; for diamond,  $\sin r = \frac{1}{2.42}$  and  $r = 24^\circ 25'$ .

This fact, that for each substance at a particular value of the angle  $r$  the angle  $i$  becomes equal to  $90^\circ$ , has an important bearing on the behavior of light when it is passing from an optically denser into an optically rarer medium.

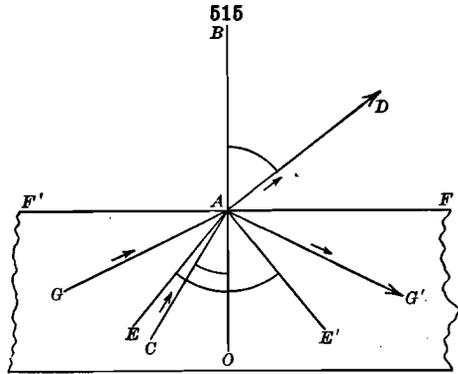
\* Phil. Trans., 163, 317, 1863.

† Wiedem. Ann., 9, 641, 1880.

‡ Wiedem. Ann., 11, 70, 1880.

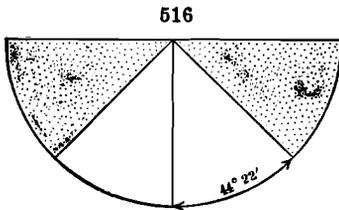
§ E. S. Larsen, Am. Jour. Sci., 23, 263, 1909. See also Cheneveau, Ann. Chem. Phys., 12, 145, 289, 1907.

In Fig. 515 we may assume that light rays coming from various directions meet the surface between a block of glass and the air at the point A. Light traveling along the path O-A will pass out into the air without a change in its direction but with an increase in its velocity. If it emerges from the glass at any other angle than 90° the ray on entering the air will be bent away from the perpendicular and the angle of deviation will vary with the angle at which the ray touched the surface and with the index of refraction of the glass. The same law holds true in this case as in the case of a ray entering from the air,

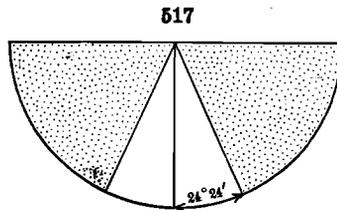


except that the formula now reads  $n = \frac{\sin r}{\sin i}$ , where  $r$  = the angle the ray in air makes with the normal to the surface and  $i$  = the angle that the ray makes within the glass to the same normal. In Fig. 515 the ray C-A will pass out into the air along the line A-D. But the angle  $i$  for the ray E-A = 38° 27' and, as shown in the preceding paragraph, for glass, where  $n = 1.608$ , the angle  $r$  in the air will be 90° and the ray will travel along the surface of the glass in the direction A-F. Consequently any ray, such as G-A, which meets the surface of the glass at an angle greater than 38° 27', will be unable to pass out into the air and will suffer *total reflection* at the surface, passing back into the glass in the direction A-G', with angle OAG = angle OAG'. The angle at which total reflection takes place for any substance is known as its *critical angle*.

The phenomenon of total reflection is taken advantage of in the cutting of gem stones. According to common practice such a stone is cut with a flat surface on top and with a number of inclined facets on the bottom. The light that enters the stone from above is in a large measure totally reflected from the sloping planes below and comes back to the eye through the stone. The amount of light reflected in this way and the consequent brilliancy of the gem increases with its index of refraction. Two stones cut exactly alike, one from diamond and the other, perhaps, from quartz, would have very different



Total Reflection in Fluorite  $n=1.43$

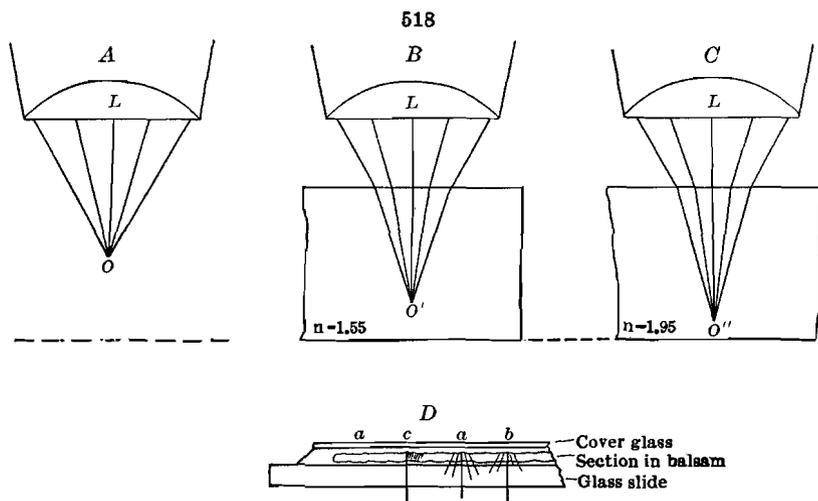


Total Reflection in Diamond  $n=2.42$

appearances due to this difference in the amount of light totally reflected from their lower facets. This principle is illustrated in Figs. 516 and 517. They

represent cross sections of two hemispheres cut, one from fluorite and the other from diamond. It is assumed that light from all directions is focused on the center of the plane surface of each hemisphere. All the light that meets this surface at an angle greater than the critical angle for the mineral will be totally reflected back through the spherical surface. The shaded areas of the figures show the amount of light in each case that would be so reflected and clearly illustrate the optical difference between the two substances.

**324. Effect of Index of Refraction upon Microscopic Phenomena.** — In the study of minerals, especially in thin sections under the microscope, variations in the index of refraction give effects which are of importance. In Fig. 518 let it be assumed that *L* is the objective lens of a compound microscope, and that the instrument is exactly focused upon a point *O*, Fig. 518, A. If now we imagine that a section of some mineral of mean index of refraction is



placed under the lens, Fig. 518, B, the point *O'* will now be in focus, or as in Fig. 518, C, where the mineral is supposed to have a high index of refraction, the focus will be at *O''*. Thus it is that with two sections of equal thickness and with the lens in the same position, one looks deeper into the mineral of higher index of refraction. Consequently, when there are two minerals in the same section, the one having a high and the other a low index of refraction (for example, a crystal of zircon,  $n = 1.95$ , embedded in quartz,  $n = 1.55$ ), the one having the higher index of refraction will apparently have the greater thickness and will appear to stand up in relief above the surface of the mineral of lower index. The apparent relief is furthermore augmented by other properties to be explained below.

In preparing thin sections of minerals or rocks for study with the microscope the process, in brief, is to make first a flat surface upon the mineral or rock by grinding it upon a plate supplied with some abrasive. This flat surface is then cemented to a piece of glass by means of Canada balsam and the remainder of the mineral is ground away until only a thin film remains, which in the best rock sections is not over 0.03 mm. in thickness. The section is finally embedded in balsam,  $n$  about 1.54, and over it a thin cover glass is laid. In

the preparation of a section the surfaces are not polished,\* hence, from the nature of the abrasive, they must be pitted and scratched and it may be assumed that in cross section such a preparation would be somewhat as represented in Fig. 518, D. When a thin section is examined under the microscope the light enters the section from below, having been reflected up into the microscope tube by an inclined mirror. Before it reaches the section it will have passed through a nicol prism and through a slightly converging lens. Let it be assumed that the mineral at *a*, Fig. 518, D, is one of mean refractive index. The convergent light entering the section will pass with little or no refraction from the mineral into the balsam because their refractive indices are nearly alike. Hence the roughness of the surface of the section is not apparent and the mineral appears as if polished. If there is a crack, as at *b*, so much light penetrates it that it is scarcely visible when the convergent lens is close to the object, but when the latter is lowered, and especially when the light is restricted by the use of an iris diaphragm inserted into the microscope tube, the nearly parallel rays of light will suffer some total reflection along the line of the crack and so make it visible. On the other hand, if the mineral has a high index of refraction there will be innumerable places all over the section where the surfaces are so inclined that the light will suffer total reflection in attempting to pass from the optically dense mineral into the rarer balsam. Hence the uneven surface of the section due to its grinding is plainly visible. This effect is more pronounced if the convergent lens is lowered. The cracks that may exist in a mineral of high index of refraction are for the same reasons much more distinct than in a mineral of low index. Further, if a mineral of high index of refraction is embedded in one of low, *c*, Fig. 518, D, there will be places along its outer edge where total reflection will take place, thus causing its outline to be dark and distinct. This effect combined with the roughened aspect of the surface and the apparent increase in thickness, as described in the preceding paragraph, all tend to make a mineral of high index of refraction stand out conspicuously in relief.

**325. Determination of the Indices of Refraction of Mineral Grains under the Microscope.** — The considerations of the preceding article suggest a means of determining the indices of refraction of mineral grains under the microscope. If a grain is immersed in a liquid of known index of refraction it is possible to determine whether it has a higher or lower index of refraction than the liquid and by the use of a series of liquids of varying refractive indices it is possible to determine with considerable accuracy the index of refraction of the mineral. A list of liquids \* in common use for such purposes, with their indices of refraction is given below.

Mixtures of refined petroleum oils and turpentine.....	1.450-1.475
Turpentine and ethylene bromide or clove oil.....	1.480-1.535
Clove oil and $\alpha$ -monobromnaphthalene.....	1.540-1.635
Petroleum oils and $\alpha$ -monobromnaphthalene.....	1.475-1.650
$\alpha$ -monobromnaphthalene and methylene iodide.....	1.650-1.740
Sulphur dissolved in methylene iodide.....	1.740-1.790
Mixtures of methylene iodide with iodides of antimony, arsenic and tin, also sulphur and iodoform (see Merwin)...	1.740-1.870
Methylene iodide and arsenic trisulphide (see Merwin).....	1.740-2.280
Resin-like substances formed from mixtures of piperine and	

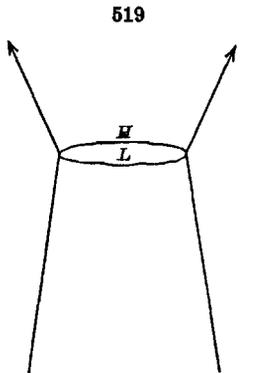
\* Wright, *Methods of Petrographic-Microscopic Research*, p. 98; Merwin, *Jour. Wash. Acad. Sc.*, 3, 35, 1913.

the tri-iodides of arsenic and antimony. These fuse easily and mineral grains can be thus embedded in a thin film of the material. . . . . 1:680-2:100

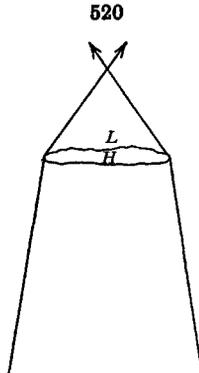
The indices of refraction of the test liquids can be determined either by the use of the total refractometer or by filling a hollow glass prism with the liquid and using the methods employed with ordinary mineral prisms, see Art. 327.

A series of these liquids should be prepared which for most purposes might conveniently show differences in the indices of the different liquids of 0.01. For more exacting work smaller differences between the indices of the members of the series would be of advantage. If these are kept in well stoppered bottles and are protected from the light they will show very little change over considerable periods of time. It is advisable, however, to check their indices at least once a year.

The mineral to be studied should be broken down into uniform small grains. (0.05 mm. is usually a good diameter) and then a few grains placed upon a glass slide. A drop of liquid with a known index of refraction is then placed upon the grains and the whole covered with a thin cover glass. When a mineral grain is immersed in a liquid of closely the same index of refraction it loses its sharpness of outline and if the mineral is colorless and the correspondence of the two indices exact it will quite disappear. Certain tests, however, are commonly used to determine the relative indices of the mineral and the liquid which with proper care can distinguish differences as small as 0.01 or with practice and especial care as small as 0.001. To make these tests the condenser below the microscope stage should be lowered and, if the instrument has a sub-stage iris diaphragm, this should be partly closed. Under these conditions the obliquity of the light is reduced and only a small pencil of light composed of nearly parallel rays enters the section. Let Fig. 519



Grain with Low Refractive Index immersed in Liquid of High Refractive Index



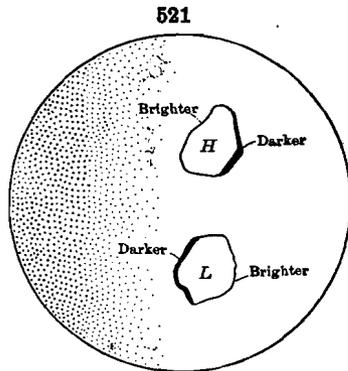
Grain with High Refractive Index immersed in Liquid of Low Refractive Index

represent a mineral grain illuminated in this way when immersed in a liquid of higher index of refraction. The light rays as they pass from the mineral into the higher refracting liquid above will be bent away from the perpendicular. In the opposite case, Fig. 520, where the mineral has the higher index the reverse will be true and the light rays will be bent toward the perpendicular. This will produce in one case a brighter illumination of the borders of the mineral grain

and in the other a brighter illumination of its center. This difference in illumination is, however, commonly so slight as to be certainly detected only with difficulty. The so-called *Becke Test* is commonly used under these circumstances. This consists in focusing upon the grain with a high power objective and then slowly raising or lowering the micro-

scope tube. In the case illustrated by Fig. 519, when the tube is raised, a narrow line of light will be seen to move outward from the mineral, while when the tube is lowered this line will move inward. In the case illustrated in Fig. 520 the opposite conditions will prevail. A convenient rule to remember is that *when the microscope tube is raised the Becke line will move toward the material of higher refractive index and when the tube is lowered this line will move toward the material of lower index.* This makes a very satisfactory and quite delicate test for distinguishing differences in refractive indices. Sometimes two lines will appear moving in opposite directions and it may be difficult to decide which is the Becke line. This is usually obviated by lowering the condenser or decreasing the aperture in the iris diaphragm. For the use of the Becke test in rock sections, see Art. 326.

The test upon mineral grains immersed in a liquid may also be made by means of oblique illumination. An oblique pencil of rays may be obtained most conveniently by placing a pencil, a finger, or a piece of cardboard between the reflecting mirror and the polarizer in such a way as to darken one-half of the field of vision. The best results will be obtained by the use of an objective of medium magnifying power. When a mineral grain is viewed under these conditions it will be noted that one of its edges is more brightly illuminated than the other. With the condenser lens lowered and mineral with a lower index of refraction than the liquid, the bright edge of the mineral will be away from the shadow, while if the mineral has a higher index than the liquid the bright edge will be on the side toward the shadow. These conditions are presented in Fig. 521, where *L* and *H* represent grains with indices respectively lower and higher than the liquid in which they are immersed. If the condenser lens is raised effects exactly opposite to those described above will be noted. It is wise, at first at least, to test the apparatus used by observing mineral fragments of known indices and taking note of the effects produced.

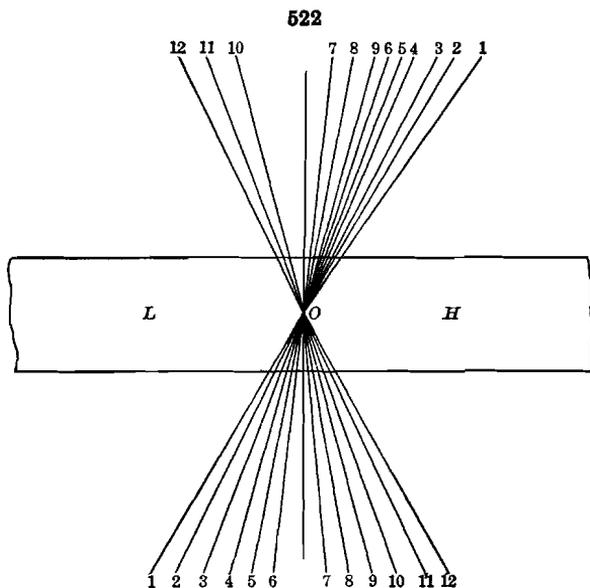


Commonly the liquids used have a higher dispersion than the mineral to be tested. In other words the liquid will have distinctly different indices of refraction for red and for blue light. If the mineral should have an index intermediate between those for red and blue light in the liquid the grain when illuminated in oblique light will show colored borders. With the condenser lens lowered the edge of the mineral next to the shadow will be colored an orange-red while the edge away from the shadow will be pale blue. If the amount of the dispersion in the liquid (*i.e.*, the difference between the indices for blue and red light) is not too great this effect gives very closely the refractive index of the mineral.

It should be pointed out here that all minerals, except those of the isometric system, show different indices of refraction depending upon the crystal direction in which the light is passing through the mineral. Consequently unorientated grains of a mineral, unless it belongs to the isometric system, will show a variation in the refractive indices depending upon their position on

the slide. Sometimes it is possible to determine the crystal orientation of a grain due to some significant cleavage or structure and so obtain the index for some particular crystal direction, but ordinarily all that can be determined is the mean index of refraction of the mineral.

**326. The Becke Test in Rock Sections.** — The Becke test can be often used in a rock section to determine the relative indices of refraction of two different minerals lying in contact with each other. Their contact plane should be nearly vertical in order to give clear results. The position of this plane can be determined by focusing on the surface of the section and then when the microscope tube is lowered note whether or not the position of the dividing line between the two minerals remains stationary or moves. If it remains stationary or moves only a little, the dividing plane is vertical or nearly so. Under these conditions assume that the cone of light entering from below is focused at point O, Fig. 522, lying on the dividing plane between L (mineral with lower index) and H (mineral with higher index). The light rays 1-6



passing as they do from a mineral of lower index into one of higher will suffer no total reflection and all emerge from the section on the side of H. On the other hand, rays 7-12 attempting to pass from H to L will only in part pass across the dividing plane while the others will be totally reflected and add themselves to rays 1-6 on the side of H. H will therefore show a brighter illumination than L. In this case also when the tube of the microscope is raised the Becke line will be seen moving toward the mineral of higher index or when the tube is lowered toward that of

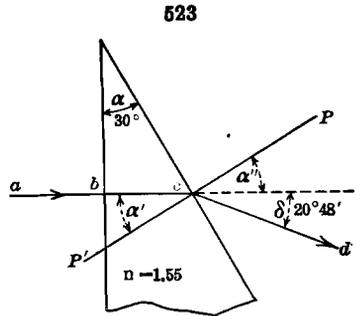
lower index. The best results will be obtained by using an objective of high magnification and the condenser lens must be lowered.

**327. Determination of the Index of Refraction by Means of Prisms or Plates.** — For the more accurate determination of the indices of refraction of minerals a natural or cut prism or plate of the mineral is used. In all cases, except minerals of the isometric system, the prism or plate used must have a certain crystallographic orientation. This matter, however, will be discussed when the optical characters of such minerals are given. For the present, we will assume that the mineral whose index of refraction is to be determined is isometric in its crystallization. There are two chief methods of determining the index of refraction by the use of a prism.

1. *The Method of Perpendicular Incidence.* — This method, although not

the one most generally employed, is an excellent one to become acquainted with, as it may be used to advantage in some cases and from it the formula necessary for making the calculations is readily derived. It is necessary to have a prism of the mineral which has two plane surfaces meeting at a small angle.

This angle should be small enough so that the light may pass freely through the prism and not suffer any total reflection as it attempts to pass out into the air. For instance with fluorite in which  $n = 1.434$ , the prism angle must be less than  $44^\circ 12'$ , for at this angle total reflection would take place. For a mineral of higher index the angle would have to be smaller still, as with diamond,  $n = 2.419$ , where total reflection would take place at  $24^\circ 24'$ . On the other hand, more accurate results will be obtained if the prism angle is fairly near to the limit of the mineral being used.<sup>3</sup>

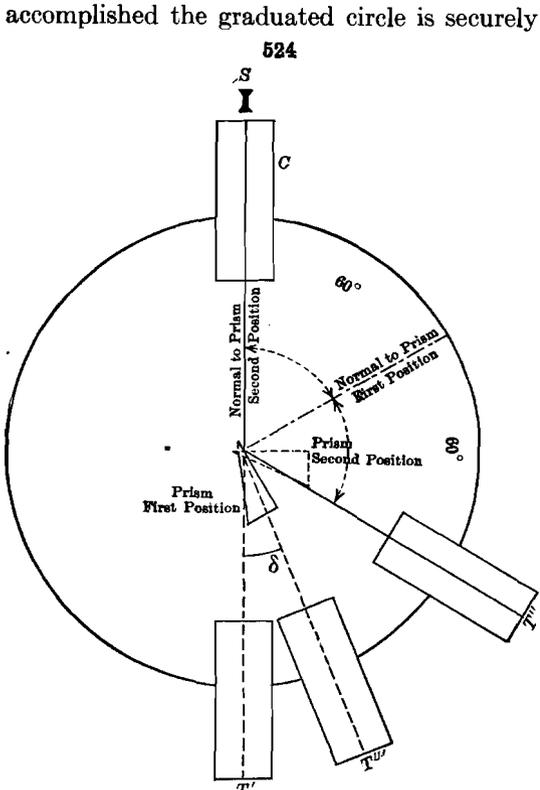


Refraction of Light through a Prism Method of Perpendicular Incidence

Let Fig. 523 represent the cross section of such a prism. Let  $a-b$  represent a ray of light striking the face of this prism at  $90^\circ$  incidence. It will suffer no deviation in its path on entering the prism but will proceed with somewhat diminished velocity until it reaches  $c$ . In passing out of the prism at this point, from a denser to a rarer medium, the light will be deflected away from the normal to the surface,  $P-P'$ , making a deviation  $\delta$  in the direction  $c-d$ . The data necessary for the calculation of the index of refraction under these conditions are the angle of the prism,  $\alpha$ , and that of the deviation in the path of the light,  $\delta$ . It is easy to see from the figure that  $\alpha$  and  $\alpha'$  are equal, for they are both parts of right-angled triangles having the angle  $bP'c$  in common, and  $\alpha''$  is equal to  $\alpha'$  because they are opposite angles. The angle of incidence, as defined in Art. 317, is equal to  $\alpha + \delta$  and the angle of refraction is equal to  $\alpha$ . Therefore the usual formula  $\frac{\sin i}{\sin r} = n$  becomes here

$\frac{\sin \alpha + \delta}{\sin \alpha} = n$ . In order to make a determination of the index of refraction, therefore, it is necessary to measure these two angles,  $\alpha$  and  $\delta$ .

The prism is mounted on a one-circle reflection goniometer and its angle  $\alpha$  measured in the same way as an angle upon a crystal. The instrument is then adapted to the uses of a refractometer. For this purpose it is necessary to note that the telescope and vernier are both fastened to the outer rim of the instrument and move together. The graduated circle being clamped, the telescope tube is first moved to the position  $T'$ , Fig. 524, so that the rays from the collimator tube,  $C$ , passing the edge of the prism, cause the light signal to fall on the vertical cross-hair of the telescope. The inner circle being clamped the telescope is next moved through an arc of exactly  $60^\circ$  to position  $T''$  and then clamped. Next the prism is turned to the first position so that the light from  $C$  is reflected from its right-hand face and the signal  $s$  falls on the cross-hair of  $T''$ . In this position the normal,  $N$ , to the prism face, must bisect the angle between the axes of  $C$  and  $T''$ . The prism is now turned through an angle of exactly  $60^\circ$  to its second position, which brings the normal  $N$  exactly in line with the axis of the collimator tube. When this has been

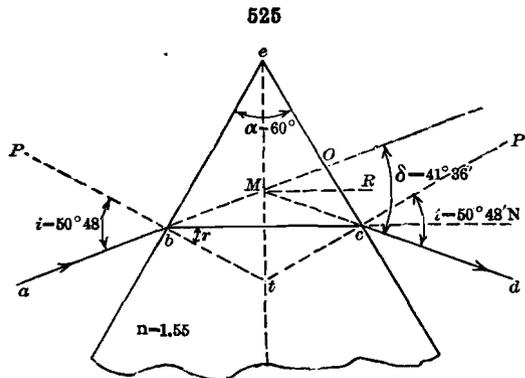


Determination of Index of Refraction  
Method of Perpendicular Incidence

generally employed for determining indices of refraction by the use of prisms. It depends upon the principle that when a beam of light, *abcd*, Fig. 525, traverses a prism in such a way that the angles *i* and *i'* are equal, the beam suffers the minimum amount of deviation in its path of any possible course through the prism. This fact may be proven empirically by experimentation on the refractometer. In order to make a determination, the angle  $\alpha$  of the prism is first measured on the goniometer. The angle of the prism with this method may be considerably larger than when the method of perpendicular

accomplished the graduated circle is securely clamped. The telescope may now be unclamped and moved without altering the position of the prism, and somewhere between *T'* and *T''* a position *T'''* will be found where the refracted ray falls on the cross-hair of the telescope. The movement of the telescope from the position *T'''* back to *T'* gives the angle of deviation, or  $\delta$ , of the light ray that has been refracted by the prism. In practice it is well to repeat the measurements both of  $\alpha$  and  $\delta$  several times and to go through all the operations of shifting the positions of the prism and telescope. If white light is used for illumination the refracted ray seen at *T'''* will appear as a narrow spectrum. To make an exact determination a monochromatic light (sodium light is best) must be employed.

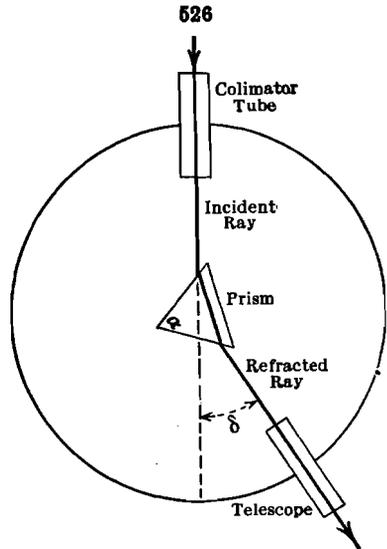
2. *The Method of Minimum Deviation.* — This is the method that is most



525

employed for determining indices of refraction by the use of prisms.

incidence is used. The prism is then turned with its edge to the left about as in the position shown in Fig. 526, the telescope unclamped and moved until the refracted ray appears in it. Now, turn the central post with the prism on it toward the left and follow the signal with the telescope. The position of minimum deviation is soon reached, when, on turning the prism, the signal seems to remain stationary for a moment and then moves away to the right, no matter in which direction the prism is turned. A little practice is needed to determine exactly the position of minimum deviation and the measurement should be made in a monochromatic light. When the telescope is properly placed at this point the graduated circle is clamped and the telescope turned until the direct signal from the collimator tube is fixed upon the vertical cross-hair. The angle between these two positions of the telescope is the same as the angle of deviation, or  $\delta$ . The formula for making the necessary calculation from these measurements follows very simply from a comparison of Figs. 525 and 523. It may be imagined that Fig. 525 is composed of two prisms like Fig. 523 placed back to back. This results in doubling the angles  $\alpha$  and  $\delta$  so that the formula now becomes

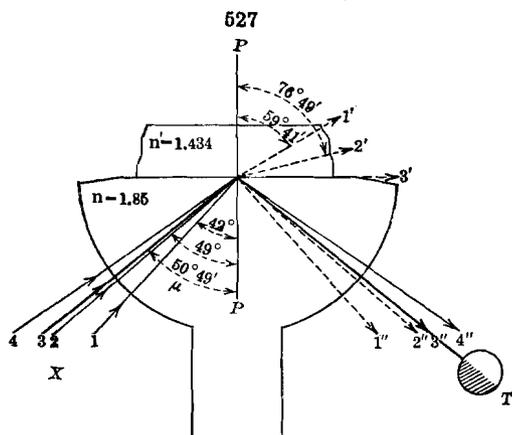


Determination of Index of Refraction  
Method of Minimum Deviation

$$n = \frac{\sin \frac{1}{2}(\alpha + \delta)}{\sin \frac{1}{2}\alpha}$$

3. *The Method of Total Reflection.* — This method is based upon the principle that light cannot always pass from an optically dense into an optically rarer medium but at a certain angle, known as the critical angle, will suffer total reflection. The critical angle for any substance varies with the index of refraction of that substance as explained in Art. 323. Consequently if we can measure this critical angle we can calculate the index of refraction of the substance. This method is particularly useful because the measurement can be made upon a single polished surface, which may be quite small in area. This measurement is made by means of an instrument, known as the Total Refractometer, a description of which will be found in Art. 352. The essential feature of this instrument is a hemisphere of glass with a known, high index of refraction. The upper surface of the hemisphere is plane and should be accurately adjusted in a horizontal position. The mineral to be tested may be of any shape provided that some surface upon it has been ground plane and polished. A drop of some liquid of high index of refraction is placed between the surface of the glass hemisphere and the flat surface of the mineral. This serves to unite the two substances and dispel the thin layer of air that would otherwise separate them. The liquid should have an index of refraction intermediate between that of the glass and that of the mineral. As the liquid

lies between the two substances in the form of a thin film with parallel surfaces whatever optical effect it has upon the light as it enters will be balanced by the opposite effect as the light leaves the film. So the optical effect of the liquid can be ignored. Fig. 527 represents a cross section of such a hemisphere with a mineral plate resting upon it. Let it be now supposed that by means of a mirror a beam of monochromatic light is thrown upon the apparatus from the direction of X. Rays 1 and 2 will suffer partial refraction at the



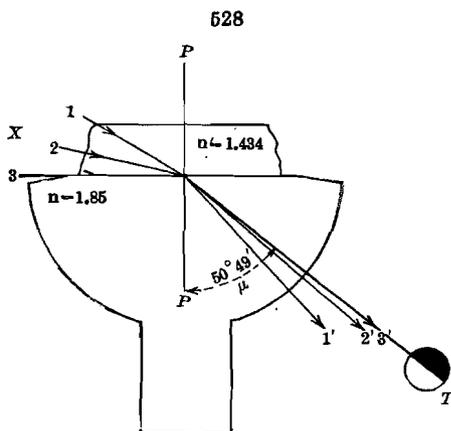
Determination of Index of Refraction  
Method of Total Reflection, I.

shadow will appear in the field of vision. One side will be illuminated by the total reflection of all rays beyond those of the critical angle while the other

side will be distinctly darker since here a considerable amount of the light passed out into the mineral. The angle between the position of the shadow and the normal to the surface of the hemisphere,  $\mu$ , Fig. 527, will be the critical angle for the combination of glass and mineral. As the index of refraction of the glass is known it is possible to calculate what the index of refraction of the mineral must be. If the mineral plate is transparent enough so that light may pass through it into the glass hemisphere another method of illumination may be used, as illustrated in Fig. 528. The reflecting mirror

is so arranged that the light comes from the direction X. Rays 1 and 2 will be refracted to 1' and 2' and 3 which just grazes the surface to 3'. Beyond this point no light will pass into the hemisphere and a telescope placed with its axis along the line 3' will show in its field a dark shadow. The contrast

dividing plane between the glass and the mineral to rays 1' and 2' and also partial reflection to rays 1'' and 2''. Ray 3 strikes the mineral at the critical angle for the combination of the glass and mineral and will in part be refracted at a 90° angle and emerge as ray 3', just grazing the surface of the hemisphere. The greater part of ray 3 will however be reflected as ray 3''. Beyond this point, all the light must be totally reflected, thus 4 to 4''. If the optical axis of a telescope is now brought to the direction 3'', what appears to be a marked



Determination of Index of Refraction  
Method of Total Reflection, II.

between the light and dark portions of the field, by this method of illumination, is much stronger than by the one first described. The telescope is so placed that the line of the shadow exactly divides the angle between the diagonal cross-hairs of the eyepiece. The telescope is attached to a graduated circle from which the angle  $\mu$  can be directly read. With each of these instruments comes ordinarily a table giving the indices of refraction corresponding to the different possible values of  $\mu$ . This table can easily be converted into a curve plotted on co-ordinate paper in such a way that the index of refraction for a particular angle can be read at a glance. Further, the calculation can be made having given the index of refraction of the glass of the hemisphere and the value of  $\mu$  for a special mineral plate. Let  $n'$  equal the index of refraction of the glass of the hemisphere and  $\mu$  the critical angle measured; then the index of refraction of the mineral,  $n$ , =  $\sin \mu \times n'$ .\*

**328. Dispersion.** — Thus far the change in direction which light suffers in reflection and refraction has alone been considered. It is further true that the amount of refraction differs for light of different wave-lengths, being greater for blue than for red. In consequence of this fact, if ordinary light be passed through a prism, as in Fig. 525, it will not only be refracted, but it will also suffer *dispersion* or be separated into its component colors, thus forming the *prismatic spectrum*.

This variation for the different colors depends directly upon their wave-lengths; the red waves are longer, their transverse vibrations are slower, and it may be shown to follow from this that they suffer less change of velocity on entering the new medium than the violet waves, which are shorter and whose velocity of transverse vibration is greater. Hence the refractive index for a given substance is greater for blue than for red light. The following are values of the refractive indices for diamond determined by Schrauf:

- 2.40845 red (lithium flame).
- 2.41723 yellow (sodium flame).
- 2.42549 green (thallium flame).

**329. Spectroscope.** — The instrument most commonly used for the analysis of the light by dispersion is familiar to all as the *spectroscope*. There

\* The derivation of this formula follows. From the ordinary law for the index of refraction we have,  $\frac{\text{velocity of light in air}}{\text{velocity of light in mineral}} = \frac{\sin i}{\sin r} = n$ . But when the critical angle is reached  $i = 90^\circ$  and  $\sin i = 1$ . Therefore we may substitute and have

$n = \frac{1}{\text{velocity of light in mineral}}$  or  $\text{velocity of light in mineral} = \frac{1}{n}$ . Further, we may derive in the same way for the highly refracting glass of the hemisphere whose refractive index,  $n'$ , is known, the expression,  $\text{velocity of light in glass} = \frac{1}{n'}$ . Further, we have in the case of the light attempting to pass from the glass (optically denser medium) into the mineral the expression,

$$\frac{\text{velocity of light in mineral}}{\text{velocity of light in glass}} = \frac{\sin 90^\circ}{\sin \mu} \text{ (measured on instrument).}$$

By substituting this becomes

$$\frac{1}{n} = \frac{\sin 90^\circ}{\sin \mu} = \frac{1}{\sin \mu} \cdot \frac{1}{n'}$$

or

$$\frac{1}{\sin \mu} = \frac{n'}{n} \text{ or } n = \sin \mu \times n'$$

are a number of varieties of spectroscopes made, the simplest of which consists of a glass prism mounted at the center of the instrument with two tubes pointing away from it. The light from the given source is received through a narrow slit in the end of one tube and made to fall as a plane-wave (that is, as a "pencil of parallel rays") upon one surface of a prism at the center. The light is dispersed by its passage through the prism and the spectrum produced is viewed through a suitable telescope at the end of the second tube.

If the light from an incandescent solid — which is "white hot" (Art. 314) — is viewed through the spectroscope, the complete band of colors of the spectrum is seen from the red through the orange, yellow, green, blue, to the violet. If, however, the light from an incandescent vapor is examined, it is found to give a spectrum consisting of bright lines (or bands) only, and these in a definite position characteristic of it — as the yellow line (double line) of sodium vapor; the more complex series of lines and bands, red, yellow, and green, characteristic of barium; the multitude of bright lines due to iron vapor (in the intensely hot electric arc), and so on.

**330. Absorption.** — Of the light incident upon the surface of a new medium, not only is part reflected (Art. 316) and part transmitted and refracted (Art. 317), but, in general, part is also *absorbed* at the surface and part also during the transmission. Physically expressed, absorption in this case means the transformation of the ether-waves into sensible heat, that is, into the motion of the molecules of the body itself.

The color of a body gives an evidence of this absorption. Thus a sheet of red glass appears red to the eye by *transmitted light*, because in the transmission of the light-waves through it, it absorbs all except those which together produce the effect of red. For the same reason a piece of jasper appears red by *reflected light*, because it absorbs part of the light-waves at the surface, or, in other words, it reflects only those which together give the effect of this particular shade of red.

Absorption in general is *selective* absorption; that is, a given body absorbs particular parts of the total radiation, or, more definitely, waves of a definite wave-length only. Thus, if transparent pieces of glass of different colors are held in succession in the path of the white light which is passing into the spectroscope, the spectrum viewed will be that due to the selective absorption of the substance in question. A layer of blood absorbs certain parts of the light so that its spectrum consists of a series of absorption bands. Certain rare substances, as the salts of didymium, etc., have the property of selective absorption in a high degree. In consequence of this, a section of a mineral containing them often gives a characteristic absorption spectrum.

This latter property may be made use of in testing certain minerals, more especially those that contain the rare earths or uranium. These give characteristic absorption bands in the spectrum. They may be tested by passing a strong white light through a thin section of the mineral and observing the resulting spectrum by means of a direct vision spectroscope. Often a better result will be obtained by illuminating the surface of the mineral and testing the reflected light for absorption bands. The light will have sufficiently penetrated the mineral before reflection to have had some of it absorbed. These tests can be made best by some sort of a microspectroscope, which will give a clear spectrum superimposed upon a scale of wave-lengths.\*

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\* For details of this method of testing minerals see Wherry, *Smithsonian Misc. Coll.*, 65, No. 5, 1915.

The dark lines of the solar spectrum, of which the so-called Fraunhofer lines are the most prominent, are due to the selective absorption exerted by the solar atmosphere upon the waves emitted by the much hotter incandescent mass of the sun.

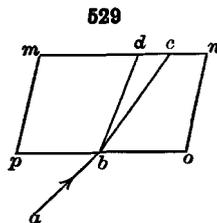
**331. Diffraction.** — When monochromatic light is made to pass through a narrow slit, or by the sharp edge of an opaque body, it suffers *diffraction*, and there arise, as may be observed upon an appropriately placed screen, a series of dark and light bands, growing fainter on the outer limits. Their presence is explained (see Arts. 335, 336) as due to the interference, or mutual reaction, of the adjoining systems of waves of light, that is, the initial light-waves, and further, those which have their origin at the edge or sides of the slit in question. It is essential that the opening in the slit should be small as compared with the wave-length of the light. If ordinary light is employed, the phenomena are the same, and for the same causes, except that the bands are successive colored spectra.

Diffraction spectra, explained on the principles alluded to, are obtained from diffraction gratings. These gratings consist of a series of extremely fine parallel lines (say, 15,000 or 20,000 to an inch) ruled with great regularity upon glass, or upon a polished surface of speculum metal. The glass grating is used with transmitted, and the speculum grating with reflected, light; the Rowland grating of the latter kind has a concave surface. Each grating gives a number of spectra, of the first, second, third order, etc. These spectra have the advantage, as compared with those given by prisms, that the dispersion of the different colors is strictly proportional to the wave-length.

**332. Double Refraction.** — As implied in Art. 320, all crystallized substances may be divided into two principal optical classes, viz.: *isotropic*, in which light has the same velocity no matter what the direction of its propagation, and *anisotropic*, in which the velocity of light in general varies with the direction of propagation. The anisotropic class is further divided into *uniaxial*, which includes crystals of the tetragonal and hexagonal systems, and *biaxial*, which includes crystals of the orthorhombic, monoclinic, and triclinic systems. The characters of these various optical classes will be explained in detail further on.

In the discussion of Art. 317, applying to isotropic media, it was shown that light-waves passing from one medium into another, which is also isotropic, suffer simply a change in wave-front in consequence of their change in velocity. In anisotropic media, however, which include all crystals but those of the isometric system, there are, in general, two wave-systems propagated with different velocities and only in certain limited cases is it true that the light-ray is normal to the wave-front. This subject cannot be adequately explained until the optical properties of these media are fully discussed, but it must be alluded to here since it serves to explain the familiar fact that, while with glass, for example, there is only one refracted ray, many other substances give two refracted rays, or, in other words, show *double refraction*.

The most familiar example of this property is furnished by the mineral calcite, also called on account of this property "doubly-refracting spar." If  $mnop$  (Fig. 529) be a cleavage piece of calcite, and a ray of light meets it at  $b$ , it will, in passing through, be divided into two rays,  $bc$ ,  $bd$ . For this reason, a dark spot or a line seen through a piece of calcite ordinarily appears double. As implied above, the same property is enjoyed by all crystallized



minerals, except those of the isometric system. The wide separation of the two refracted rays by calcite, which makes the phenomenon so striking, is a consequence of the large difference in the values of its indices of refraction; in other words, as technically expressed, it is due to the *strength* of its double refraction, or its *birefringence*.

**333.** Double refraction also takes place in the anisotropic media just mentioned, in the majority of cases, even when the incident light is perpendicular to the surface. If the medium belongs to the uniaxial class (see p. 253, *et seq.*), one of the rays always retains its initial direction normal to the surface; but the other, except in certain special cases, is more or less deviated from it. With a biaxial substance, further, both rays are usually refracted and bent from their original direction. In the case of both uniaxial and biaxial media, however, it is still true that the normal to the wave-front remains unrefracted with perpendicular incidence.

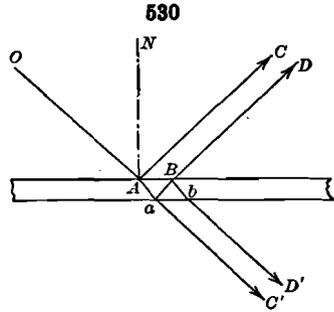
**334. Interference of Waves in General.** — The subject of the interference of light-waves, alluded to in Art. 331, requires detailed discussion. It is one of great importance, since it serves to explain many common and beautiful phenomena in the optical study of crystals.

Referring again to the water-waves spoken of in Art. 308, it is easily understood that when two wave-systems, going out, for example, from two centers of disturbance near one another, come together, if at a given point they meet in the same phase (as crest to crest), the result is to give the particle in question a double amplitude of motion. On the other hand, if at any point the two wave-systems come together in opposite phases, that is, half a wave-length apart, the crest of one corresponding to the trough of the other, they interfere and the amplitude of motion is zero. Under certain conditions, therefore, two sets of waves may unite to form waves of double amplitude; on the other hand, they may mutually interfere and destroy each other. Obviously an indefinite number of intermediate cases lie between these extremes. What is true of the waves mentioned is true also of sound-waves and of wave-motion in general. A very simple case of interference was spoken of in connection with the discussion of the waves carried by a long rope (Art. 310).

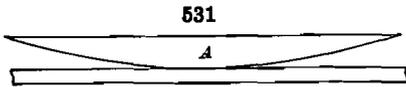
**335. Interference of Light-waves.** — Interference phenomena can be most satisfactorily studied in the case of light-waves. The extreme cases are as follows: If two waves of like length and intensity, and propagated in the same direction, meet in the same phase, they unite to form a wave of double intensity (double amplitude). This, as stated in Art. 311, will cause an increase in the intensity of the light. If, however, the waves differ in phase by half a wave-length, or an odd multiple of this, they *interfere* and extinguish each other and no light results. For other relations of phase they are also said to interfere, forming a new resultant wave, differing in amplitude from each of the component waves. In the above cases monochromatic light-waves were assumed (that is, those of like length). If ordinary white light is used interference for certain wave-lengths may result with the consequent subtraction of the corresponding color from the white light and so give rise to various spectrum colors.

**336. Illustrations of Interference.** — A simple illustration is afforded by the bright colors of very thin films or plates, as a film of oil on water, a soap-bubble, and like cases. To understand these, it is only necessary to remember that the incident light-waves are reflected in part from the upper and in part from the lower surface of the film or plate. The rays that are reflected from

the under surface of the very thin film (see Fig. 530) having traveled a greater distance and with a different velocity will, when they unite with those rays reflected from the upper surface, show in general a different phase. For some particular wave-length of light this difference is likely to be exactly a half wave-length or some odd multiple of this amount and so the corresponding color will be eliminated (assuming that ordinary white light is being used) and its complementary color will be seen. It is to be noted that the phenomena of interference by reflection are somewhat complicated by the fact that there is a reversal of phase (that is, a loss of half a wave-length) at the surface that separates the medium of greater optical density from the rarer one. Hence the actual relation in phase of the two reflected rays, as  $AC$ ,  $BD$  (supposing them of the same wave-length)



due to the greater length of path traversed by  $BD$ , together with the loss of a half wave-length due to the reversal of phase spoken of. As shown in the



figure, there are also two transmitted waves which also interfere in like manner. A plano-convex lens of long curvature, resting on a plane glass surface (Fig. 531), and hence separated from it, except at the center, by a film of air of varying thickness, gives by reflected monochromatic light a dark center and about this a series of light and dark rings, called *Newton's rings*. The dark center is due to the interference of the incident and reflected waves, the later half a wave-length behind the former. The light rings correspond to the distances where the two sets of reflected waves meet in the *same phase*, that is (noting the explanation above) where the retardation of those having the longer path is a half wave-length or an odd multiple of this ( $\frac{1}{2}\lambda$ ,  $\frac{3}{2}\lambda$ ,  $\frac{5}{2}\lambda$ , etc.). Similarly the dark rings fall between these and correspond to the points where the two waves meet in *opposite phase*, the retardation being a wave-length or an even multiple of this. The rings are closer together with blue than with red because of the smaller wave-length of blue light. In each of the cases described the ring is properly the intersection on the plane surface of the cone of rays of like retardation.

In ordinary white light we get, instead of the alternate light and dark rings described above, a series of colored bands. If the illumination was originally by sodium light the position of the dark rings indicates where light for that particular wave-length has been extinguished through interference. When white light is used the conditions in respect to its component having the yellow sodium-light wave-length have not changed and this light will still be eliminated at the same points, but now, instead of dark rings, we get rings having the complementary color blue. If our original illumination was by means of a red light the dark rings would have had different positions from those produced in sodium light. And again when white light is used red light is eliminated at those points and its complementary color shows. In this way we obtain a series of *colored rings*, each showing the successive colors of the spectrum. The series of the spectrum colors are repeated a number of times

due to successive interferences produced by differences of phase of  $\frac{1}{2}$ ,  $1\frac{1}{2}$ ,  $2\frac{1}{2}$ , etc., wave-lengths. The different series are distinguished as of the first, second, third, etc., order; for a given color, as red, may be repeated a number of times. The interference rings for different colored lights are not evenly spaced, the rings shown in blue light being, for instance, closer together than for red. Consequently after three or four repetitions of the spectrum bands the different interference rings begin to overlap one another and the resulting colors become fainter and less pure. Ultimately this overlapping becomes so general that the effect of color is lost and white light, the so-called white of the higher orders, is shown.

Another most satisfactory illustration of the interference of light-waves is given by means of the diffraction gratings spoken of in Art. 331.

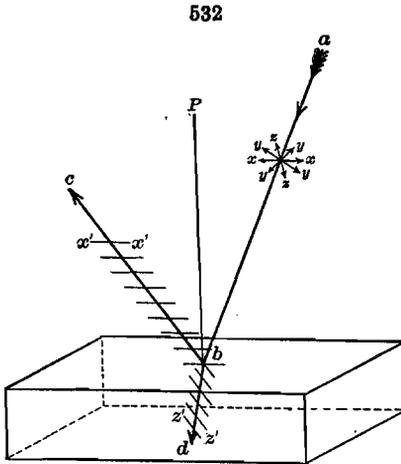
Other cases of the composition of two systems of light-waves will be considered after some remarks on polarized light.

**337. Polarization and Polarized Light.** — Ordinary light is propagated by transverse vibrations of the ether which may take place in any direction as long as it is at right angles to the line of propagation. The direction of vibration is constantly changing and the resulting disturbance of the ether is a complex one. A ray of ordinary light will be symmetrical, therefore, only to the line of its propagation.

*Plane-polarized light*, on the other hand, as stated briefly in Art. 311, is propagated by ether-vibrations which take place *in one plane only*. The change by which ordinary light is converted into a polarized light is called *polarization*, and the plane at right angles to the plane of transverse vibration is called the *plane of polarization*.\*

Polarization may be accomplished (1) by reflection and by single refraction, and (2) by double refraction.

**338. Polarization by Reflection and Single Refraction.** — In general,

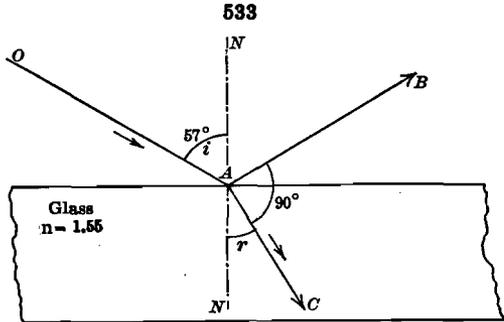


light which has suffered reflection from a surface like that of polished glass is more or less completely polarized; that is, the reflected waves are propagated by vibrations to a large extent limited to a single plane, viz., (as assumed) the plane normal to the plane of incidence, which last is hence the plane of polarization. Furthermore, in this case, the light transmitted and refracted by the reflecting medium is also in like manner partially polarized; that is, the vibrations are more or less limited to a single plane, in this case a plane at right angles to the former and hence coinciding with the plane of incidence. For instance, in Fig. 532, let *a-b* represent an incident light ray in which

the vibrations are taking place in all possible transverse directions as represented

\* It is necessary to keep clear the distinction between the *plane of polarization* and the plane in which the vibrations take place. All ambiguity is avoided by speaking uniformly of the *vibration-plane* of the light.

by the arrows,  $x-x$ ,  $y-y$ , and  $z-z$ . When this ray strikes the polished surface at  $b$  light with vibrations parallel to  $x-x$  will be reflected along  $b-c$  and other vibrations near to  $x-x$  in direction will be shifted to this direction so that the reflected ray will be largely polarized. In a similar manner the light having  $z-z$  vibrations will enter the transparent substance as the refracted ray  $b-d$  and other vibrations will be shifted to this direction so that the refracted ray is also largely polarized and in a plane at right angles to that of the reflected ray. Light reflected from a polished and transparent surface is not completely polarized but there is an angle of incidence for every substance at which the amount of polarization will be at its maximum. This will happen, as illustrated in Fig. 533, when the angle between the reflected and refracted rays  $AB$  and  $AC$  equals  $90^\circ$ . It is evident from a consideration of



Brewster's Law

the figure that the angle  $r$  is the complement of  $i$ ; hence the formula  $\frac{\sin i}{\sin r} = n$  becomes in this case

$$\frac{\sin i}{\cos i} = \tan i = n.$$

This law, established by Brewster, may be stated as follows:

*The angle of incidence for maximum polarization is that angle whose tangent is the index of refraction of the reflecting substance.* For crown glass this angle is about  $57^\circ$  (see Fig. 533). If light suffers repeated reflections from a series of thin glass plates, the polarization is more complete, though its intensity is weakened. Metallic surfaces polarize the light very slightly.

**339. Polarization by Double Refraction.** — When light in passing through a crystalline medium is doubly refracted (Art. 332) or divided into two sets of waves, it is always true that both are completely polarized and in planes at right angles to each other. This subject can only be satisfactorily explained after a full discussion of the properties of anisotropic crystalline media, but it may be alluded to here since this principle gives the most satisfactory method of obtaining polarized light. For this end it is necessary that one of the two wave-systems should be extinguished, so that only that one due to a single set of vibrations is transmitted. This is accomplished by natural absorption in the case of tourmaline plates and by artificial means in the Nicol prisms of calcite.

**340. Polarized Light by Absorption.** — Light passing through a strongly colored but transparent thin section of a tourmaline crystal — the section being cut parallel to the vertical crystallographic axis — will be almost completely polarized. This can be easily demonstrated in the following way. Select a polished floor surface, or a table top and stand in such a position that light from a window is reflected from the polished wood to the eye. Look at this reflected light through the tourmaline section, holding it first with the

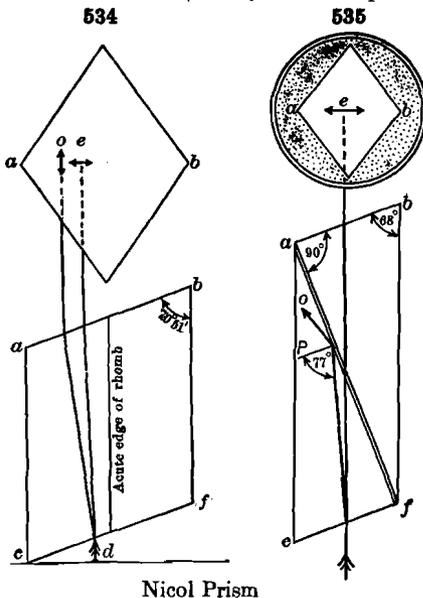
direction of the *c* crystal axis in a horizontal position and then turning the section until the *c* axis becomes vertical. The light passing into the tourmaline section is in considerable part polarized through its reflection from the wood surface and possesses a horizontal vibration direction. It will be noted that when the *c* axis of the tourmaline is horizontal the section readily transmits light but when this axis is vertical the section becomes practically opaque. The crystal structure of the tourmaline is such that light entering it is broken up into two rays (*i.e.*, it is doubly refracted), one of which has its vibrations parallel to the *c* axis, while the vibrations of the other lie in the plane of the horizontal crystal axes. From the foregoing experiment it is obvious that the light vibrating parallel to the *c* axis is readily transmitted by the crystal but that the other ray, vibrating in the horizontal axial plane, is almost completely absorbed. Under these conditions it is clear that the transmitted light belongs almost wholly to one ray, the vibrations of which take place in a single direction. In other words, the light transmitted by such a tourmaline section is *polarized*.

If two such sections of tourmaline are available it is instructive to make the following experiment with them. Place them together, first with their *c* axes parallel to each other, and then turn one section upon the other until these axes are at right angles to each other. In the first case, the light comes through the sections because the vibration planes of the transmitted rays in the two sections are parallel to each other. In the second case, all light is cut off because now these two vibration planes are at right angles to each other, the light that did get through the first section being wholly absorbed in the second.

**341. Polarized Light by Double Refraction.** — Calcite, as already stated in Art. 332, possesses in an unusual degree the power to doubly refract light. If we take a cleavage block of clear calcite (Iceland spar) and look at an image through it, such as a dot or line drawn on a piece of paper, the image will appear double. If we take a card and make in it a pinhole, place the card upon one face of a cleavage rhombohedron and, looking through the calcite, hold it up against a source of light, we will observe two bright dots. Now if we look in the same way at the light reflected from a polished wooden surface, as described in the preceding article, we will find that when a line bisecting the acute angles of the rhombic face of the cleavage block is horizontal one of these images is bright while the other is almost invisible. If we then turn the block so that the line bisecting the obtuse angles of the rhombic face is horizontal the first image will fade while the second becomes bright. Remembering that the light reflected from the polished wooden surface is largely polarized with a horizontal vibration direction, it becomes evident from this experiment that the two rays into which the light is broken up in passing through the calcite are polarized and that their planes of vibration are at right angles to each other and respectively bisect the angles of the rhombic face of the cleavage block. As the double refraction of calcite is strong, it follows that the indices of refraction of the two rays show considerable differences. This fact is taken advantage of in constructing a prism from calcite in such a way as to wholly eliminate one of these rays and so, as only the other ray can come through the prism, effectively polarizing the light that emerges.

The prism referred to above is called the *Nicol Prism* or simply the *nicol*. A full explanation of the nicol cannot be made at this time, as there would be required a knowledge of the optical properties of hexagonal crystals, but a

description may be given enabling one to understand its construction and uses. In Fig. 534 is represented a cleavage rhombohedron of calcite with its edges vertical. Let  $d$  represent a point of light underneath the rhombohedron. Light coming from  $d$  will be broken into two rays whose paths through the rhombohedron are shown by the lines  $o$  and  $e$ . As shown above, these two rays are polarized, with vibration directions as indicated by the double arrows in the top view in Fig. 534. In the construction of a nicol, the top and bottom surfaces of such a cleavage rhombohedron are ground and polished so that they make angles of  $68^\circ$  with the vertical edges. Then the block is cut in two along the diagonal  $a-f$ , as shown in Fig. 535. These two surfaces, after being polished, are cemented together by means of a thin layer of Canada balsam. Let us assume that a ray of light enters the prism from below, as shown in Fig. 535. It is broken up into the rays  $o$  and  $e$ . The ray  $o$  travels with the slower velocity, has therefore the higher index of refraction, and shows a greater deviation from the original path. The Canada balsam has a lower index of refraction than ray  $o$ , which, therefore, when it strikes the layer of balsam, is attempting to pass from an optically dense into a rarer medium. The construction of the prism is such that this ray meets the layer of balsam at an angle greater than the critical angle for this optical combination and suffers total reflection toward the side of the prism, and will be absorbed by whatever fastening holds the nicol. The second ray  $e$  passes through the prism with almost no deviation from its original course. Its index of refraction and that of the Canada balsam are nearly the same, hence the ray suffers almost no deflection at this point and passes out of the upper face of the prism. The light, therefore, that emerges from a nicol belongs wholly to one ray and is all vibrating parallel to the shorter diagonal of the rhombic end surface. It should be noted, however, that some prisms are made in a different way and that the above statement concerning the plane of vibration of the light emerging from the prism may not always hold true. It is always wise to test the plane of vibration of a nicol by looking through it at the floor or a table top as previously described. The prism will show bright when its plane of vibration is horizontal, thus corresponding to the plane of vibration of the reflected light.

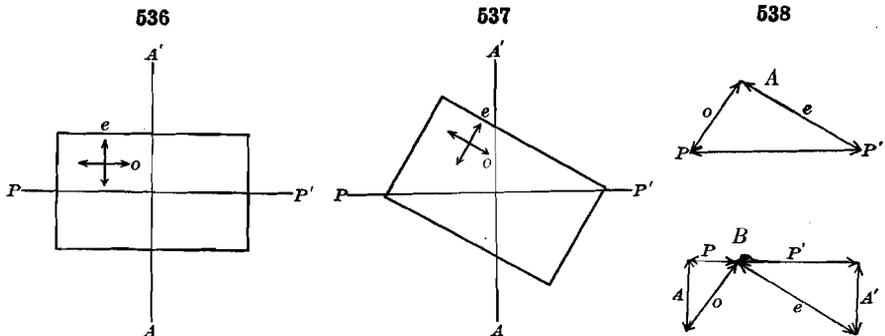


Nicol Prism

**342. Polariscopes. Polarizer. Analyzer.** — The combination of two nicols, or other polarizing contrivances, between which transparent mineral sections may be examined in polarized light is called, in general, a *polariscope*; the common forms of which are described later. In any polariscope the lower prism, or other contrivance, which polarizes the light given from the outside source is called the *polarizer*; the upper prism is the *analyser*. If these prisms

have their vibration-planes at right angles to each other, they are said to be *crossed*; the incident light polarized by the polarizer will then be extinguished by the analyzer; briefly, under these conditions it is said to suffer *extinction*.

**343. Interference of Plane-polarized Waves. Interference Colors.**—When sections of doubly refracting minerals are examined in polarized light certain interference effects are commonly obtained that are of great importance. As shown in Art. 341, calcite when it doubly refracts light also polarizes the two rays and in planes that are at right angles to each other. In general, this is true of sections of doubly refracting minerals. Consider, then, what takes place when a general section of a doubly refracting mineral is placed in a polariscope between the polarizer and analyzer the planes of vibration of which are at right angles to each other. In Fig. 536 let the rectangular outline represent such a section. The double arrows marked *o* and *e* show the two possible directions of vibration of light in the section. The direction *P-P'* represents the plane of vibration of light which emerges from the polarizer below and *A-A'* shows the direction in which light must vibrate when it emerges from the analyzer above. In the first case to be considered the directions *o* and *e* are taken as parallel to *P-P'* and *A-A'* respectively. The light that enters the section from below must all vibrate parallel to the direction *P-P'*. It enters the mineral section and must vibrate there as the ray labeled *o*. There will be no ray in the mineral vibrating parallel to the direction *e*, as a vibration parallel to *o* cannot be resolved into another at right angles to it. The light will leave the section, therefore, still vibrating parallel to *P-P'* and enter the analyzer above. It will, however, be entirely reflected in the analyzer at the layer of balsam since only light vibrating parallel to *A-A'*, which is at right angles to *P-P'*, can emerge from the analyzer. Consequently, when such a section has its planes of vibration parallel to those of the polarizer and analyzer, the section will appear dark. The same reasoning holds true when the section is turned to a position at 90° from the first. Consequently with such a section there are four positions at 90° to each other in which it appears dark during its complete rotation upon the stage of the polariscope. At such positions the section, is said to be *extinguished*.



Next consider what happens when the vibration directions of the section are at oblique angles to those of the polarizer and analyzer. In Fig. 537 let *o* and *e* represent the directions of vibration in a section which makes some oblique angle with the directions *P-P'* and *A-A'*. In Fig. 538A let the line *P-P'* represent the direction and amplitude of the vibration of the light enter-

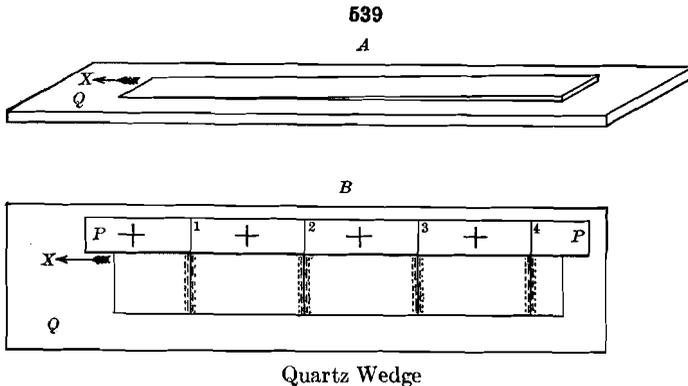
ing the mineral section having come through the polarizer below. The light must vibrate in the mineral in directions parallel to  $o$  and  $e$ , Fig. 537. The vibration  $P-P'$  will therefore be resolved into two vibrations at right angles to each other which will be parallel respectively to  $o$  and  $e$ . In Fig. 538A the lines  $o$  and  $e$  representing the direction and amplitudes of such vibrations are found by the application of the principle of the parallelogram of forces. The two rays emerge from the mineral section vibrating in these two planes and enter the analyzer above. Since the planes of vibration in the analyzer are parallel to  $A-A'$  and  $P-P'$  these two rays  $o$  and  $e$  will resolve each into two new rays which will vibrate now parallel to  $A-A'$  and  $P-P'$ . The two rays labeled  $P$  and  $P'$  in Fig. 538B will be absorbed by the analyzer but the rays marked  $A$  and  $A'$  will emerge and meet the eye. The section in this position, therefore, will be illuminated. Consequently the section will be illuminated in all possible positions in which the directions of vibration of the light in the mineral make inclined angles with the directions of vibration of the polarizer and analyzer. It is easy to prove that this illumination will be at its maximum when the angle between the directions  $o$  and  $e$  and  $A-A'$  and  $P-P'$  is  $45^\circ$ . In addition to being illuminated, the section, if thin, will also be colored. This interference color, as it is called, of mineral sections when examined in a polariscope, now needs explanation.

The amount of refraction which any ray of light suffers on entering a mineral depends upon two things, namely, the angle of incidence at which the light enters and the index of refraction of the mineral. In the case of a doubly refracting mineral we have a light ray entering the section at a given angle of incidence and then being broken up into two polarized rays which have different angles of refraction and so travel different paths. Consequently the indices of refraction for these rays must be different and from this it follows that the two rays must have different velocities and will therefore emerge from the mineral in different phases. Light waves having different phases will in a greater or less degree interfere with each other and in case of light of certain wave-lengths, *i.e.*, light of some particular color, the interference may lead to extinguishment of that particular wave-length. If one particular color is subtracted in this way from white light the result will be to produce the complementary color and under such conditions the section will no longer be white but colored. The color of thin sections of minerals when seen under the polariscope is known as their *interference color*. To develop this subject further use will be made of an accessory of the microscope known as the Quartz Wedge.

The *Quartz Wedge* consists simply of a very thin tapering wedge the faces of which are approximately parallel to the prism of a quartz crystal. It is mounted on a narrow glass plate, Fig. 539, A. The plate is generally marked with the letter  $Q$  (quartz) and with an arrow. If the wedge is cut, as is usually the case, with its longer direction at right angles to the vertical axis of a quartz crystal, the arrow is marked  $X$  (or  $\alpha$ ), which indicates that of the two directions of vibration of light in the wedge the one which is parallel to this direction is that of the ray which is propagated with greater velocity. Some wedges are cut with their longer direction parallel to the vertical axis of quartz, and the arrow in this case would be marked  $Z$  (or  $\epsilon$ ), which indicates that this is the direction of vibration of the slower ray. It is absolutely essential that the optical orientation of the wedge be known.

The quartz wedge furnishes a prismatic section of varying thickness and

of known orientation and may be used to study the effects of polarized light on plates (short sections of the wedge) of different thicknesses. Take the simplest form of polariscope, a combination of polarizer and analyzer without

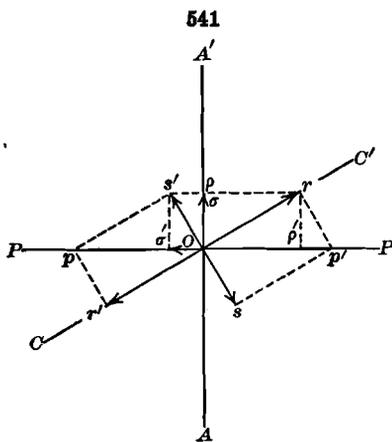
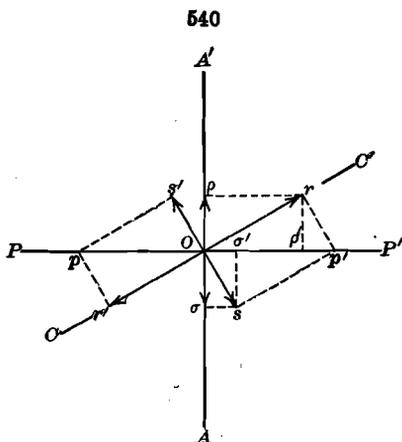


lenses, and arrange it so that the vibration planes of the instrument are crossed. Illuminate with ordinary light and on the stage of the instrument place a quartz wedge with its  $X$  direction parallel to the plane of vibration of the polarizer. The light in entering the quartz will vibrate parallel to the  $X$  direction and without changing its plane of vibration will pass through the quartz and up into the upper nicol where it will suffer total reflection. Hence the wedge in this position will appear dark throughout its length. A similar result will be obtained when the  $X$  direction of the wedge is placed parallel to the vibration plane of the analyzer. But if the wedge is turned so that its  $X$  direction makes an angle of about  $45^\circ$  with the plane of vibration of the polarizer the wedge will exhibit a series of beautiful interference colors, arranged in transverse bands, the nature of which will be discussed in a later paragraph. If the wedge is turned from this  $45^\circ$  position the colors become less and less brilliant as the position of extinction is neared.

As preliminary to another experiment, paste a narrow strip of paper,  $P-P'$ , Fig. 539, B, on the top, but to one side, of a quartz wedge. Place this on the stage of a polariscope (without lenses) and illuminate with diffused sodium light. When the wedge is examined under these conditions it will be found that it shows extinction when its vibration directions are parallel to those of the polariscope but at the  $45^\circ$  position it will show transverse dark bands upon a yellow field. The number of these bands will depend upon the thickness of the wedge; usually there will be two or three, although for this experiment it is interesting to have a longer and proportionally thicker wedge than those commonly supplied, so as to have more bands appearing. Mark on the strip of paper the position of each band, as illustrated in Fig. 539, B and number them, starting at the band nearest the thinner end of the wedge. The number 1 band marks the place where the faster of the two rays, into which the quartz breaks up the sodium light, has gained exactly one wave length in its phase over the slower ray. At the point marked 2 the gain is two wave-lengths, etc.

In explaining the phenomenon just described, reference is made to Fig. 540 in which it is assumed that  $P-P'$  is the plane of the polarizer and  $A-A'$

is the plane of the analyzer, and a quartz wedge is between them at such an angle that the direction of the vertical crystal axis lies parallel to  $C-C'$ . If we explain the action of light in the wedge in a purely mechanical way we may say, let the amplitude of vibration of an ether particle before the light has entered the wedge be represented in the figure by the line  $O-p$ . The vibration may be likened to that of a pendulum, swinging back and forth from  $p$  to  $p'$ . If the impact, or disturbance, of an ether particle is communicated to the ether particles of the quartz when it is at  $O$  at the middle of an oscillation from  $p$  to  $p'$ , there will result two disturbances, one to  $r$  parallel to  $C-C'$  and the other to  $s$  at right angles thereto. The amplitude of the vibrations represented by  $O-r$  and  $O-s$  are determined by the parallelogram of forces, as indicated by the dotted lines in the figure. During the passage of these two rays through the quartz the one whose vibrations are represented by  $s-s'$  travels the faster and it is assumed that the thickness of the quartz wedge at the place under consideration is such that, on emerging, this ray is just one wave-length ahead of the one whose vibrations are parallel to  $r-r'$ . Now, when one ray is exactly one wavelength ahead of another (it may be two, three or any exact number of wavelengths) the conditions are such, that, at the middle of the vibration, when an ether particle of the ray  $s-s'$  is just starting from  $O$  to  $s$ , an ether particle of the ray  $r-r'$  will be just starting from  $O$  to  $r$ . Now consider the effects produced by the simultaneous impacts in the directions  $O$  to  $s$  and  $O$  to  $r$  upon the ether particles of the calcite constituting the analyzer. A vibration from  $s'$  to  $s$  acting at  $O$  will displace the ether particles of the calcite to  $\sigma$  and  $\sigma'$ . Likewise a vibration from  $r'$  to  $r$  acting at  $O$  will displace the ether particles to  $\rho$  and  $\rho'$ . Two of these resulting disturbances, namely  $O-\sigma'$  and  $O-\rho'$ , are easily disposed of, for being in the plane  $P-P'$  their effects cannot pass beyond the layer of Canada balsam in the nicol. The other disturbances  $O-\sigma$  and  $O-\rho$  are both in the plane  $A-A'$  and can emerge from the nicol, but since the ether particles at  $O$  are acted upon simultaneously by forces of equal magnitude acting in opposite directions no disturbance can take place and under these conditions the section is dark. From the above it

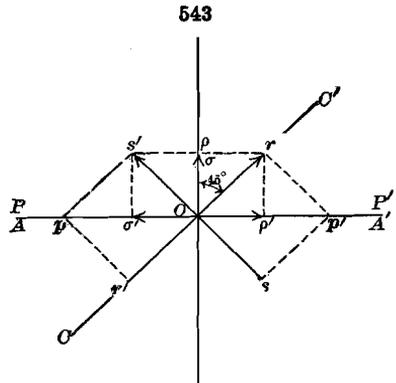
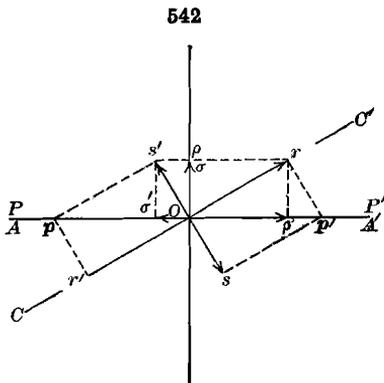


follows that, when a section of a doubly refracting mineral is observed between crossed nicols with its vibration planes making some oblique angle

with the vibration planes of the nicols, complete interference will take place for some particular wave-length of light whenever the two polarized rays corresponding to this color emerge from the section in the same phase.

It is well to consider next the effects that result when, with the planes of vibration of the nicols crossed, light travels through such thicknesses of the quartz wedge that one ray gains  $\frac{1}{2}$ ,  $\frac{3}{4}$ , or some other half wave-length over the second ray. Let it be supposed, Fig. 541, that at  $O$ , the middle of an oscillation from  $p$  to  $p'$ , the impact is communicated to the ether particles of a quartz section the vertical crystal axis of which lies parallel to the direction  $C-C'$ . There will result two disturbances in the quartz, one from  $O$  to  $r$  and the other from  $O$  to  $s$ . After traversing the section the phases of the two rays differ by one half wave-length so that when the direction of the first oscillation is from  $O$  to  $r$ , that of the other will be from  $O$  to  $s'$ . The impulse  $O-r$  gives rise in the analyzer to two disturbances  $O-\rho$  and  $O-\rho'$ . The impulse  $O-s'$  results in the two displacements  $O-\sigma$  and  $O-\sigma'$ . Of these disturbances  $O-\rho'$  and  $O-\sigma'$  do not extend beyond the layer of Canada balsam of the analyzer, while  $O-\rho$  and  $O-\sigma$ , both of equal magnitude and vibrating in the plane  $A-A'$ , are additive and give rise to a disturbance and the sensation of light. Hence, in the experiment with the quartz wedge in sodium light, there are areas of light between the dark bands, Fig. 539, B.

An instructive experiment with the wedge should also be tried with sodium light illumination but with the planes of vibration of the polariscope parallel to each other instead of crossed as in the previous cases. If light traverses such a thickness of quartz that, on emerging, one ray has gained one half of a wave-length over the other the conditions up to the time the vibrations enter the analyzer will be the same as in the previous case. The vibrations, however, which can now pass through the analyzer result, Fig. 542, from the disturbances  $O-\rho'$  and  $O-\sigma'$ , and these acting on an ether particle in opposite directions but with unequal force would produce a disturbance in the direction  $O-\rho'$  and, therefore, give rise to the sensation of light. A wedge with the direction of the vertical crystal axis about parallel to  $C-C'$  will appear yellow throughout its entire length. This will not be the case, however, if the wedge is turned so that the vertical axis



makes an angle of 45 with the plane of polarization, Fig. 543, for then the forces acting upon an ether particle at  $O$  are  $O-\rho'$  and  $O-\sigma$ , which, being equal

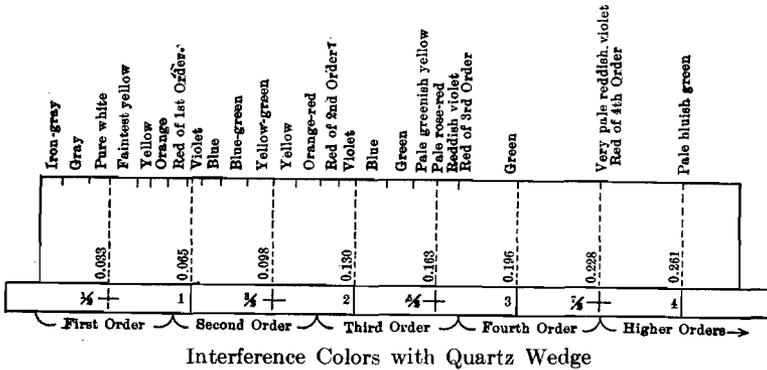
and in opposite directions, will neutralize each other and therefore will not produce any sensation of light. A wedge in the  $45^\circ$  position will therefore show a series of dark bands, the first, starting from the thin end of the wedge, being where one ray has gained  $\frac{1}{2}$  wave-length, the second where it has gained  $\frac{3}{2}$  wave-lengths, etc., over the second ray. In Fig. 539, B, the positions of the bands in this experiment are indicated by the crosses marked on the strip of paper pasted upon one side of the quartz wedge. The lines and crosses on this paper strip indicating gains of whole and one half wave-lengths for yellow light may now serve as starting points for further considerations.

For the next experiment use a microscope with crossed nicols, a number 3 or 4 objective, and illuminate with ordinary light; place the wedge in the  $45^\circ$  position and focus on that part of it opposite the first line drawn on the paper strip. The field will show at its center a blue color, about at the point where it is beginning to merge into red. A moment's consideration will indicate what this color really is. It is a mixture of all colors of the spectrum except yellow. That this is the case may be proved by analyzing the blue by means of a small direct-vision spectroscope. This will show a spectrum through which runs a dark band between the red and green, that is, where the yellow would normally appear. The blue of the wedge at this point is therefore the complement of yellow, which has been made to disappear by interference. Next focus the microscope on the wedge opposite the second line. Here the color will be nearly a sky blue, with perhaps a tinge of green. Upon analysis with the spectroscope again a dark band will be found in the yellow, this time due to interference brought about by a difference in phase of two wave-lengths for sodium light. Proceeding next to opposite the third line the color will be found to be a light green, which on analysis shows a band where yellow should occur and a perceptible shortening of the spectrum, especially by cutting off the extreme blue and violet. Opposite the fourth line the color would be a very pale green which upon analysis with the spectroscope would show two dark bands, one in the yellow and another in the blue. The pale green color is therefore due to a mixture of red, green, and violet. If, in the original experiment the wedge had been illuminated by a monochromatic blue light it would have been found at the thicker end of the wedge, where the fourth band for yellow light was located, there would have been a fifth band for the blue light. Consequently the interference color at this point of the wedge is equivalent to white light from which both yellow and blue have been subtracted. If a wedge of extra length was available for study it would have been noted that opposite the eighth band for sodium light the color showing, when the wedge is studied in the polarizing microscope, was white. This upon analysis would show a spectrum crossed by bands in the red, yellow, green, and blue. In other words, in traversing the thickness of the quartz at this point, the faster ray has gained for red seven wave-lengths over the slower ray, for yellow eight, for green nine, for blue ten. The white polarization effect seen when looking at this point with the microscope is known as white of the higher order. It is a mixture of the several primary colors of the spectrum, some portions of all of which are present and combine to give the effect of white.

It is important to study carefully the polarization colors of the quartz wedge under the microscope, using Fig. 544 as a guide. It will be noted that the colors occur in general in the following order as the thickness of the quartz increases: violet, blue, green, yellow, orange, red. This sequence of colors is repeated quite distinctly three times and then as the thicker end of the wedge

is approached the colors become fainter and not so clear. This series of interference colors is divided into orders as indicated in Fig. 544. It is to be

544



noted that at the very thin end of the wedge before any interference can have taken place the color is white. Also the thicker end of the wedge is white because here there is an overlapping of the various points of interference of the different colors. The thickness of the wedge at the different points is given in millimeters in Fig. 544.

**344. Sensitive Tint.** — Among the accessories of the polarizing microscope is a thin plate of gypsum mounted between two plates of glass. It is commonly marked S. T. and also with an arrow marked either X (α) or Z (ε), indicating respectively the direction of vibration of the faster or slower ray. If this is placed on the microscope stage in the 45° position with the nicols crossed, the interference color shown is reddish violet, the same as that close to the red of the first order of the quartz wedge. It is an interesting experiment to first put a quartz wedge under the microscope and focus on the red-violet, just beyond the red of the first order and then cover it with the sensitive tint arranged in such a way that its X direction is at right angles to the X direction of the quartz wedge. The resulting color will be gray. The explanation of this is simple. Whatever gain the faster ray had made over the slower in passing through the quartz has been overcome or neutralized by passing through a layer of gypsum of opposite optical orientation and of suitable thickness to produce the same interference as the quartz. The name *Sensitive Tint* is given to this gypsum plate because a slight increase of the double refraction which it shows will give a blue color while a corresponding slight decrease will change the color to yellow. Numerous uses of the sensitive tint will be given in subsequent articles.

**345. Interference Colors of Mineral Sections.** — The interference colors of mineral sections depend upon three things.

1. On the strength of the birefringence of the mineral, or in other words upon the amount of double refraction that the mineral shows. The greater the birefringence the higher the order of interference color, the other influencing factors remaining constant.

2. The thickness of the section. The thicker the section the greater will be the amount of double refraction and consequently the higher the order of the interference color.

3. The crystallographic orientation of the section. This will be explained later when the optical characters of the different crystal systems are described.

**346. Determination of the Order of the Interference Color of a Mineral Section.** — It is often important to determine to which order (see last paragraph of Art. 343) the interference color of a given section belongs. If, as is often the case, the section has somewhere a tapering wedge-like edge, the successive bands of color shown there can be counted and the order of the color of the surface of the section determined. In other words the order of the color can be told in the same way as upon the quartz wedge itself. If such an edge cannot be found the quartz wedge is used as described below.

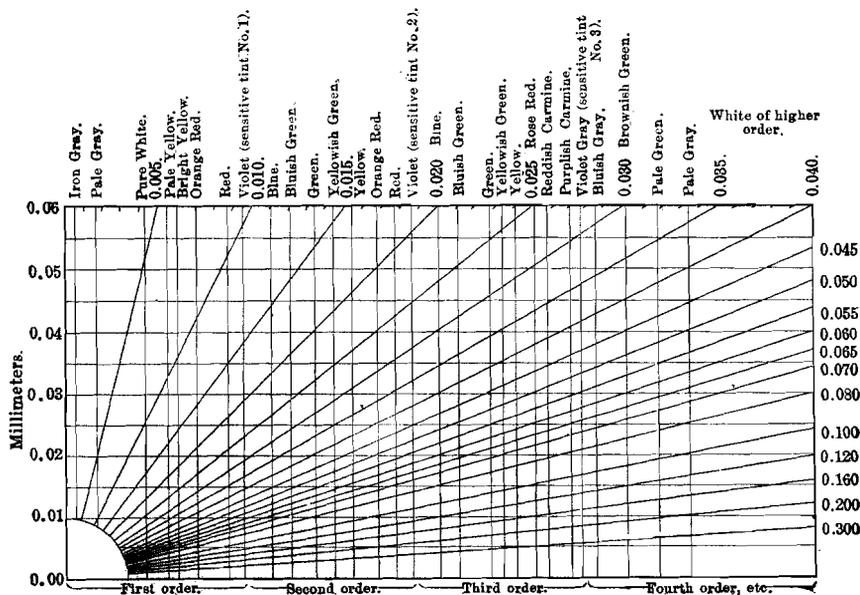
Suppose a certain mineral section showed an interference color of orange-red and it was desired to ascertain whether this color belonged to the first or second order. Under the microscope with crossed nicols find a position of extinction of the section and then turn it upon the stage of the microscope through an angle of  $45^\circ$ . By doing this the vibration directions of the section are brought into such a position that they make angles of  $45^\circ$  with the vibration directions of the polarizer and analyzer. Then insert above the section and below the analyzer a quartz wedge, the optical orientation of which is known. A slot running through the microscope tube just above the objective and making an angle of  $45^\circ$  to the cross-hairs is provided for this purpose.

Under these conditions there are two possibilities. Either the optical orientation of the section and the quartz wedge agree; *i.e.*, the *X* direction of the section is parallel to the *X* direction of the wedge, or these two directions are at right angles to each other. The effect of the introduction of the wedge above the section will be either to increase or decrease the amount of double refraction of the light due to the mineral section. If the double refraction is increased, the optical effect will be as if the mineral section had been thickened and in this case its interference color will rise in its order. On the other hand, if the double refraction of the light is decreased by the introduction of the quartz wedge the effect will be as if the mineral section had been thinned and the interference color will fall in its order. In the first case the red interference color of the section would be changed as the wedge is pushed in, first to blue and then to green. In the second case it would change to orange, then to yellow and green. Arrange the section, therefore, so that upon the introduction of the quartz wedge the interference color will fall in its order. Then gradually continue to push in the wedge, noting the successive colors that occur as the amount of the double refraction is decreased. Finally the point will be reached where the thickness of the wedge will give practically the same amount of double refraction as the mineral section. The two having opposite optical orientations the result will be to eliminate all interference and a gray color of the first order will result. When this condition arises the quartz wedge is said to *compensate the mineral*. By noting the succession of colors that occurs until this point is reached the order of the original color of the section can be determined.

**347. Determination of Strength of Birefringence.** — The birefringence, or amount of double refraction, varies with different minerals. It is expressed numerically by a figure that is the difference between the greatest and least indices of refraction of a given mineral. In the case of calcite, for instance, the index of refraction for one ray is 1.486 and for the other is 1.658. The birefringence of calcite therefore equals 0.172. This is much higher than for most minerals, the strength of the birefringence of quartz being only 0.0091.

An accurate estimation of the strength of the birefringence of a mineral is to be made only by determining the greatest and least indices of refraction. An approximate determination, however, can often be made in a thin section under the microscope. The order of the interference color of a section, as stated in Art. 345, varies with the thickness of the mineral, its crystallographic orientation and the strength of its birefringence. If the first two factors are known the birefringence can be estimated by noting the interference color of the section. Fig. 545 will aid in this determination. The thickness of the section is shown in the column at the left. The strength of the birefringence is expressed along the top and right-hand side of the figure. Suppose that a given section was 0.03 mm. in thickness and showed an orange-red interference color of the first order. By following the diagonal line that crosses the horizontal line marked 0.03 mm. at a point lying in the middle of the orange-red of the first order it will be seen that the birefringence of the mineral must be about 0.015. This method of determining birefringence is most commonly used in the case of minerals observed in rock sections. In the case of the best rock sections the thickness of the section is usually about 0.03 to 0.04 mm. The thickness of the section can also be judged from the interference color shown by some known mineral, like quartz or feldspar, which is to be observed in the section. As the strength of the birefringence of a mineral varies with its crystallographic orientation it is necessary always to look over the rock section and use in the observations that section of the mineral which shows the highest order of interference color. The birefringence of a mineral is always

545



Determination of the Strength of Birefringence (after Pirsson and Robinson)

expressed as the maximum difference between the indices of refraction. Consequently, with a uniform thickness, such as is obtained in a rock section, that

section of a mineral which shows the highest order of interference color most nearly approaches the proper orientation for the maximum birefringence.

The order of the interference color of a given section is to be determined by the method of compensation as explained in Art. 346. Special quartz wedges are made with scales upon them giving the birefringence produced by the varying thicknesses of the wedge. If such a wedge is available it is only necessary to note the birefringence corresponding to that thickness of the quartz which produced compensation. This will obviously equal the birefringence of the section being tested. For a detailed description of the various wedges and compensators used for this purpose the reader must be referred to more special text-books.\*

**348. Determination of the Relative Optical Character of the Extinction Directions of any Section of a Doubly Refracting Mineral.** — It frequently becomes important to determine which of the two rays of light in a doubly refracting mineral is being propagated with the greater or less velocity; in other words, to determine which of the two directions of vibration corresponds to the *X* and which to the *Z* direction. Place the given section under the microscope with the nicols crossed. Find a position of extinction and then turn the section through an arc of  $45^\circ$  so that its vibration directions make that angle with the planes of vibration of the nicols. If the section in this position shows a strong color or white of the higher order the quartz wedge is used. The optical orientation of the wedge must be known, *i.e.*, which are its *X* and *Z* directions. The wedge is then pushed through the slot above the objective lens, the thin end of the wedge being introduced first. The vibration directions of the wedge and the section will now coincide and the effect of the gradual introduction of the wedge above the mineral will be to slowly increase or decrease the birefringence due to the section. The result will be to either raise or lower the order of the interference color obtained. If the *X* directions of the wedge and the section coincide the effect will be additive in character and the color will rise in its order. If the optical directions of the two are opposed to each other the birefringence is decreased and the color will fall. By noting which effect takes place the *X* and *Z* directions of the section are determined.

In this use of the quartz wedge the following precaution must be observed. If the section originally showed a color of the first order and the wedge was introduced in the opposed position the effect would be to cause the color to fall rapidly to gray of the first order. The optical effect of the quartz wedge would thus quickly compensate that of the section. From this point on as the quartz wedge is pushed further in, the optical effect of the wedge will more and more preponderate over that of the section and the interference colors will now appear in ascending order. Under these conditions, if the first effect of the quartz wedge was overlooked, a wrong deduction would be made. It is always best to repeat the test with the section rotated  $90^\circ$  from the first position. The two results should be of opposite character and so serve to confirm each other.

Frequently a thick section of a mineral will show a tapering edge somewhere which will show bands of color. When the quartz wedge is introduced above the section these color bands will move, either toward the center of the section,

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\* See Johannsen, *Manual of Petrographic Methods*; Wright, *The Methods of Petrographic-Microscopic Research*.

or go off toward the edge. When the color bands move up on the section it means that the effect of the quartz wedge is such that a thicker part of the section is now showing the same interference as a thinner part did originally. In other words, the result is as if the section had been thinned. If this is so, then the *X* and *Z* directions of the section and the wedge must be opposed to each other. On the other hand, if the color bands move off the section it means that a thinner part of the section is showing the same interference effect that a thicker portion did originally. The introduction of the quartz wedge has in effect thickened the section and therefore the similar optical directions of the two coincide. This test is particularly useful for determining the *X* and *Z* directions of deeply colored minerals, as the natural color of the mineral may, over the thicker portion of the section, completely mask the interference color.

If a mineral section shows an interference color of white or gray of the first order the sensitive tint will give better results than the quartz wedge. If the similar optical directions of the section and the sensitive tint coincide the effect will be to raise the color of the sensitive tint (red of the first order) to blue. On the other hand, if the optical orientations of the two are opposed the color will fall to yellow. This test can be made to advantage only when the birefringent effect of the section is small enough to just raise or lower the color of the sensitive tint respectively to blue or yellow.

**349. Circularly and Elliptically Polarized Light.** In the preceding articles the two interfering light-rays, after emerging from the second nicol, were assumed to be polarized in the same plane; for them the resulting phenomena as indicated are comparatively simple. If, however, two plane-polarized rays propagated in the same direction have their vibration-directions at right angles to each other, and if they differ one-quarter of a wave-length ( $\frac{1}{4}\lambda$ ) in phase (assuming monochromatic light), then it may be shown that the composition of these two systems results in a ray of *circularly polarized* light. Briefly expressed, this is a ray that, looked at end-on, would seem to be propagated by ether-vibrations taking place in circles about the line of transmission. From the side, the onward motion would be like that of a screw, and either right-handed or left-handed.

If, again, two light-rays meet as above described, with a difference of phase differing from  $\frac{1}{4}\lambda$  (but not equal to an even multiple of  $\frac{1}{2}\lambda$ ), then the resulting composition gives rise to *elliptically polarized* light, that is, a light-ray propagated by ether-motions taking place in ellipses.

The above results are obtained most simply by passing plane-polarized light through a doubly refracting medium of the proper thickness (*e.g.*, a mica plate) which is placed with its vibration-planes inclined  $45^\circ$  to that of the polarizer. If the thickness is such as to give a difference in phase of  $\frac{1}{4}\lambda$  or an odd multiple of this, the light which emerges is circularly polarized. If the phase differs from  $\frac{1}{4}\lambda$  (but is not equal to  $\frac{1}{2}\lambda$  or  $\lambda$ ), the emergent light is elliptically polarized.

**350. Rotation of Plane of Polarization.** — In the case of certain doubly refracting crystallized media (as quartz), and also of certain solutions (as of sugar), it can be shown that the light is propagated by two sets of ether-vibrations which take place, not in definite transverse planes — as in plane-polarized light — but in circles; that is, each ray is circularly polarized, one being right-handed, the other left-handed. Further, of these rays, one will uniformly gain with reference to the other. The result is, that if a ray of

plane-polarized light fall upon such a medium (assuming the simplest case, as of a section of quartz cut normal to the vertical crystal axis), it is found that the two rays circularly polarized within unite on emerging to a plane-polarized ray, but the plane of polarization has suffered an angular change or rotation, which may be either to the right (to one looking in the direction of the ray), when the substance is said to be *right-handed*, or to the left, when it is called *left-handed*.

This phenomenon is theoretically possible with all crystals of a given system belonging to any of the classes of lower symmetry than the normal class which show a plagiohedral development of the faces\*; or, more simply, those in which the corresponding right and left (or + and -) typical forms are enantiomorphous (pp. 71, 112), as noted in the chapter on crystallography. In mineralogy, this subject is most important with the common species quartz, of the rhombohedral-trapezohedral class, and a further discussion of it is postponed to a later page (Art. 394).

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## OPTICAL INSTRUMENTS AND METHODS

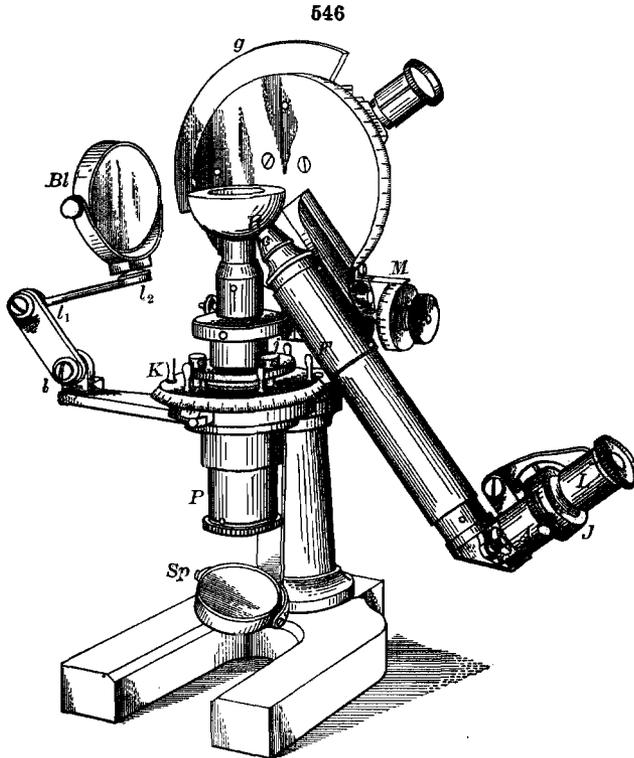
**351. Measurement of Refractive Indices. Refractometer.** — For the determination of the refractive indices of crystallized minerals various methods are employed. The most accurate results, when suitable material is at hand, may be obtained by the ordinary refractometer. This requires the observation of the angle of minimum deviation ( $\delta$ ) of a light-ray on passing through a prism of the given material, having a known angle ( $\alpha$ ), and with its edge cut in the proper direction. The measurements of  $\alpha$  and  $\delta$  can be made with an ordinary refractometer or with the horizontal goniometer described in Art. 231. For the latter instrument, the collimator is made stationary, being fastened to a leg of the tripod support, but the observing telescope with the verniers moves freely. Further, for this object the graduated circle is clamped, and the screw attachments connected with the axis carrying the support, and the vernier circle and observing telescope are loosened. Light from a monochromatic source passes through an appropriate slit and an image of this is thrown by the collimator upon the prism. With a doubly refracting substance two images are yielded and the angle of minimum deviation must be measured for each; the proper direction for the edge of the prism in this case is discussed later. When  $\alpha$  and  $\delta$  are known the formula in Art. 327 is used.

**352. Total Refractometer.** — The principle of total reflection (Art. 323) may also be made use of to determine the refractive index. No prism is required, but only a small fragment having a single polished surface; this may have any direction with an isometric crystal, but in other cases must have a definite orientation, as described later. A number of different instruments have been devised by means of which indices of refraction may be measured by the use of total reflection. A type widely used at present is represented in Fig. 546. This particular instrument was made by Leiss. It consists of a hemisphere of glass ( $H$ ) having a high refractive index which is mounted upon a glass post through which light may be reflected from the mirror  $Sp$ . The

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\* Of the thirty-two possible classes among crystals, the following eleven may be characterized by circular polarization: Class 4, p. 71; 5, p. 72; 11 and 12, p. 89; 17, p. 102; 22, p. 112; 23 and 24, p. 114; 27, p. 128; 29, p. 138; 32, p. 147.

tube *P* contains a nicol prism so that when a thin section of a mineral is placed upon the plane surface of the hemisphere it is possible to obtain its optical orientation in the same manner as with the polarizing microscope. The



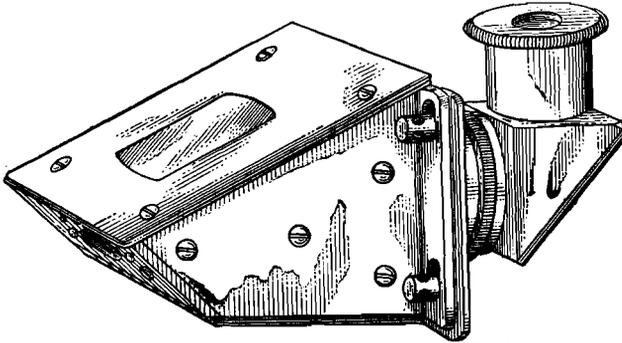
Total Refractometer

polished mineral surface is placed upon the plane surface of *H* with a film of some high refracting oil between them. Then a beam of light from some source of illumination, usually a monochromatic light, is reflected by means of the mirror *Bl* in such a way as to produce a total reflection shadow down on the opposite side of the hemisphere. For further details of the operation see Art. 327. The telescope *F* is attached to the disk *V* which in turn carries a scale on its edge. The telescope is moved up or down until the line between the light and dark portions of the field lies on the cross-hairs. The angle which is read on the scale under these conditions is the desired critical angle for the combination of the glass of the hemisphere and the mineral plate. Knowing this angle and the index of refraction of the glass of the hemisphere it is possible to calculate the index of refraction of the mineral; see Art. 327. Usually a table is furnished with the total refractometer by means of which the desired refractive index is obtained directly from the value of the measured critical angle. The post carrying the glass hemisphere may be revolved in the horizontal plane and the angle of rotation measured on the scale *K*. This permits the measurement of indices corresponding to different vibration directions in the mineral. *L* is an eye lens which in combination with the other lenses of the tube *F* makes a low power microscope, which is used in the preliminary operations in order to center the mineral plate, etc. In the tube *A* is an iris diaphragm and usually a small nicol prism that may be pushed in or out of the tube.

Fig. 547 represents a small total refractometer devised by G. F. H. Smith which depends upon the same principle. The mineral plate is placed upon the glass surface shown on the top of the instrument. The instrument is so

held that light enters at the forward end, and the totally reflected light is sent by means of an inclined mirror to the eyepiece. A scale is placed in the instru-

547

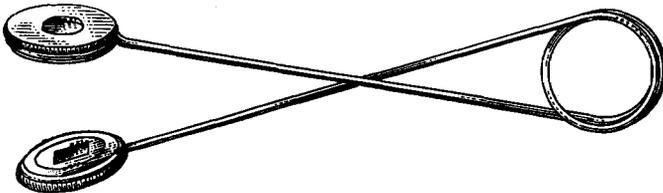


Smith Total Refractometer (Actual Size)

ment in such a way that the boundary between the light and dark areas is seen superimposed upon it and so yields directly the value of the refractive index. For rapid and approximate determinations this instrument is very useful.

**353. Tourmaline Tong.** — A very simple form of polariscope for converging light is shown in Fig. 548; it is convenient in use, but of limited application. Here the polarizer and analyzer are two tourmaline plates such as were described in Art. 340. They are mounted in pieces of cork and held in a kind of wire pincers. The object to be examined is placed between them and supported there by the spring in the wire. In use they are held close to the eye, and in this position the crystal section is viewed in *converging* polarized light, with the result of showing (under proper conditions) the axial interference-figures (Arts. 389 and 407).

548



Tourmaline Tong

**354. Polariscope. Conoscope.** — The common forms of polariscopes employing nicol prisms are shown in Figs. 549 and 550.\* Fig. 549 represents the instrument arranged for converging light, which is often called a *conoscope*.

The essential parts are the mirror *S*, reflecting the light, which after passing through the lens *e* is polarized by the prism *p*. It is then rendered strongly converging by the system of lenses *nn*, before passing through the section under examination placed on a plate at *k*. This plate can be revolved

\* These figures are taken from the catalogue of Fuess.

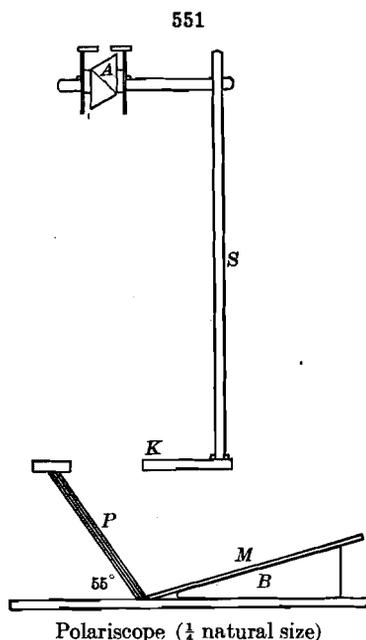


Fig. 551 represents in cross-section a simple, inexpensive but quite efficient form of polariscope. The polarizing device, *P*, is in the form of two or three thin glass sheets, the back of the bottom one being blackened. These glass plates are set at the appropriate angle to secure the maximum amount of polarization of the light reflected from them up through the opening in the stage *K*. *M* represents an adjustable mirror by means of which light is reflected upon *P*. The analyzer, *A*, is a small nicol prism which is held over the opening in the stage by means of the standard *S*. A double series of lenses may be placed upon the stage of the instrument and so convert it into a conoscope.

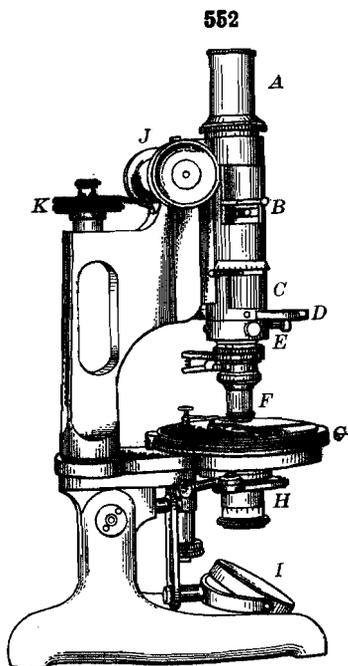
**355. Polarization - Microscope.** — The investigation of the form and optical properties of minerals when in microscopic form has been much facilitated by the use of microscopes\* specially adapted for this purpose. First arranged with reference to the special study of minerals as seen in thin sections of rocks, they have now been so elaborated as largely to take the place of the older optical instruments. They not only allow of the determination of the optical properties of minerals with greater facility, but are applicable to many cases where the crystals in hand are far too small for other means.

A highly serviceable microscope is the Laboratory Model made by the Bausch and Lomb Optical Co., and illustrated in Fig. 552. The essential arrangements of this instrument are as follows: The eyepiece at *A*, which is removable, contains the cross-hairs with an eye lens adjustable for focusing upon them. At *B* is a Bertrand lens that slides in and out of the tube, with an iris diaphragm immediately above it. At *C* is the analyzer box which slides in and out of the body tube. This prism may be revolved through a quarter turn. *D* is a slot in the microscope tube with a dust-proof shutter for the introduction of various accessories, such as the quartz wedge, etc. At *E* is the nosepiece which can be centered by the two screws which work at right angles in the *N* and *E* positions. The objective *F* is held in place by a spring clamp and is quickly detached. The stage, *G*, revolves and carries a scale graduated into degrees, the attached vernier permitting the reading of angles to one-tenth degree. The substage at *H* carries condensing lenses, iris diaphragm and the polarizing prism. It can be moved upward and downward by means of a screw-head and when at its lowest point can be sprung to one side, out of the optical axis. The mirror at *I* is adjustable and has both a plane and concave surface. The coarse focusing adjustment is at *J*, while the milled head at *K* provides a fine adjustment by means of which a vertical movement of 0.0005 mm. can be read.

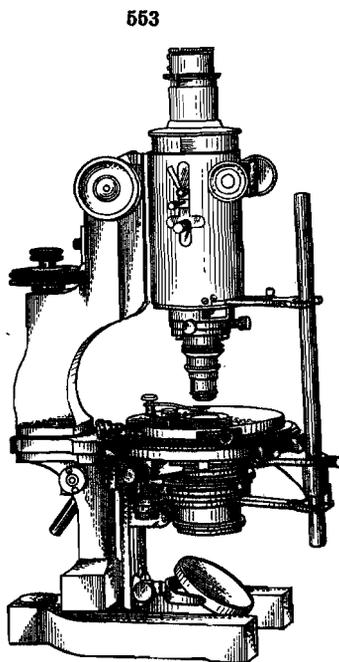
\* For detailed descriptions of the polarizing microscope and its accessories see Johannsen, *Manual of Petrographic Methods*; Wright, *The Methods of Petrographic Research*; etc.



356. The Research Model of the Bausch and Lomb microscope is illustrated in Fig. 553. This instrument is patterned after one described by



Petrographical Microscope  
(Laboratory Model, Bausch and  
Lomb,  $\frac{1}{2}$  actual size)



Petrographical Microscope  
(Research Model, Bausch and  
Lomb  $\frac{1}{2}$  actual size)

Wright to whose papers reference is made for a more detailed account. The outstanding features of the instrument may be briefly summarized as follows: It has a large body-tube within which are always contained the analyzer and the Bertrand lens, both when they lie in or outside the optical axis of the microscope. The two nicols may be connected by means of the upright bar and rotated simultaneously through an arc of  $90^\circ$ . This enables the measurement of extinction angles, etc., to be made without the necessity of revolving the stage and the consequent difficulty in keeping the mineral grain under observation exactly centered in the field. This bar carries verniers that lie against the scale engraved upon the stage so that the angle of rotation of the nicols can be accurately measured. The polarizing prism can be entirely removed from the optical axis. A revolvable carrier for a sensitive plate is attached to the iris diaphragm mount of the substage.

### GENERAL OPTICAL CHARACTERS OF MINERALS

357. There are certain characteristics belonging to all minerals alike, crystallized and non-crystallized, in their relation to light. These are:

1. DIAPHANEITY: depending on the relative quantity of light transmitted.

2. **COLOR:** depending on the kind of light reflected or transmitted, as determined by the selective absorption.
3. **LUSTER:** depending on the power and manner of reflecting light.

### 1. DIAPHANEITY

**358. Degrees of Transparency.** — The amount of light transmitted by a solid varies in intensity, or, in other words, more or less light may be *absorbed* in the passage through the given substance (see Art. 330). The amount of absorption is a minimum in a transparent solid, as ice, while it is greatest in one which is opaque, as iron. The following terms are adopted to express the different degrees in the power of transmitting light:

*Transparent:* when the outline of an object seen through the mineral is perfectly distinct.

*Subtransparent, or semi-transparent:* when objects are seen, but the outlines are not distinct.

*Translucent:* when light is transmitted, but objects are not seen.

*Subtranslucent:* when merely the edges transmit light or are translucent.

When no light is transmitted, even on the thin edges of small splinters, the mineral is said to be *opaque*. This is properly only a *relative* term, since no substance fails to transmit some light, if made sufficiently thin. Magnetite is translucent in the Pennsbury mica. Even gold may be beaten out so thin as to be translucent, in which case it transmits a greenish light.

The property of diaphaneity occurs in the mineral kingdom, from nearly perfect opacity to transparency, and many minerals present, in their numerous varieties, nearly all the different degrees.

### 2. COLOR

**359. Nature of Color.** — As briefly explained in Art. 314, the sensation of color depends, in the case of monochromatic light, solely upon the length of the waves of light which meet the eye. If the light consists of various wave-lengths, it is to the combined effect of these that the sensation of color is due.

Further, since the light ordinarily employed is essentially white light, that is, consists of all the wave-lengths corresponding to the successive colors of the spectrum, the color of a body depends upon the selective absorption (see Art. 330) which it exerts upon the light transmitted or reflected by it. A yellow mineral, for instance, absorbs all the waves of the spectrum with the exception of those which together give the sensation of yellow. In general, the color which the eye perceives is the result of the mixture of those waves which are not absorbed.

**360. Streak.** — The color of the powder of a mineral as obtained by scratching the surface of the mineral with a knife or file, or, still better, if the mineral is not too hard, by rubbing it on an unglazed porcelain surface, is called the *streak*. The streak is often a very important quality in distinguishing minerals. This is especially true with minerals having a metallic luster, as defined in Art. 364.

**361. Dichroism; Pleochroism.** — The selective absorption, to which the color of a mineral is due, more especially by transmitted light, often varies with the crystallographic direction in which the light passes through the mineral. It is hence one of the special optical characters depending upon the

crystallization, which are discussed later. Here belong *dichroism* or *pleochroism*, the property of exhibiting different colors in different crystallographic directions by transmitted light. This subject is explained further in Arts. 398 and 411.

**362. Varieties of Color.** — The following eight colors were selected by Werner as fundamental, to facilitate the employment of this character in the description of minerals: *white, gray, black, blue, green, yellow, red, and brown.*

(a) The varieties of METALLIC COLORS recognized are as follows:

1. *Copper-red*: native copper. — 2. *Bronze-yellow*: pyrrhotite. — 3. *Brass-yellow*: chalcopyrite. — 4. *Gold-yellow*: native gold. — 5. *Silver-white*: native silver, less distinct in arsenopyrite. — 6. *Tin-white*: mercury; cobaltite. — 7. *Lead-gray*: galena, molybdenite. — 8. *Steel-gray*: nearly the color of fine-grained steel on a recent fracture; native platinum, and palladium.

(b) The following are the varieties of NON-METALLIC COLORS:

A. WHITE. 1. *Snow-white*: Carrara marble. — 2. *Reddish white*, 3. *Yellowish white* and 4. *Grayish white*: all illustrated by some varieties of calcite and quartz. — 5. *Greenish white*: talc. — 6. *Milk white*: white, slightly bluish; some chalcedony.

B. GRAY. 1. *Bluish gray*: gray, inclining to dirty blue. — 2. *Pearl-gray*: gray, mixed with red and blue; cerargyrite. — 3. *Smoke-gray*: gray, with some brown; flint. — 4. *Greenish gray*: gray, with some green; cat's-eye; some varieties of talc. — 5. *Yellowish gray*: some varieties of compact limestone. — 6. *Ash-gray*: the purest gray color; zoisite.

C. BLACK. 1. *Grayish black*: black, mixed with gray (without green, brown, or blue tints); basalt; Lydian stone. — 2. *Velvet-black*: pure black; obsidian, black tourmaline. — 3. *Greenish black*: augite. — 4. *Brownish black*: brown coal, lignite. — 5. *Bluish black*: black cobalt.

D. BLUE. 1. *Blackish blue*: dark varieties of azurite. — 2. *Azure-blue*: a clear shade of bright blue; pale varieties of azurite, bright varieties of lazulite. — 3. *Violet-blue*: blue, mixed with red; amethyst, fluorite. — 4. *Lavender-blue*: blue, with some red and much gray. — 5. *Prussian-blue*, or Berlin blue: pure blue; sapphire, cyanite. — 6. *Small-blue*: some varieties of gypsum. — 7. *Indigo-blue*: blue, with black and green; blue tourmaline. — 8. *Sky-blue*: pale blue, with a little green; it is called mountain-blue by painters.

E. GREEN. 1. *Verdigris-green*: green, inclining to blue; some feldspar (amazon-stone). — 2. *Celandine-green*: green, with blue and gray; some varieties of talc and beryl. It is the color of the leaves of the celandine. — 3. *Mountain-green*: green, with much blue; beryl. — 4. *Leek-green*: green, with some brown; the color of leaves of garlic; distinctly seen in prase, a variety of quartz. — 5. *Emerald-green*: pure deep green; emerald. — 6. *Apple-green*: light green with some yellow; chrysoptase. — 7. *Grass-green*: bright green, with more yellow; green diallage. — 8. *Pistachio-green*: yellowish green, with some brown; epidote. — 9. *Asparagus-green*: pale green, with much yellow; asparagus stone (apatite). — 10. *Blackish green*: serpentine. — 11. *Olive-green*: dark green, with much brown and yellow; chrysolite. — 12. *Oil-green*: the color of olive-oil; beryl, pitchstone. — 13. *Siskin-green*: light green, much inclining to yellow; uranite.

F. YELLOW. 1. *Sulphur-yellow*: sulphur. — 2. *Straw-yellow*: pale yellow; topaz. — 3. *Wax-yellow*: grayish yellow with some brown; sphalerite, opal. — 4. *Honey-yellow*: yellow, with some red and brown; calcite. — 5. *Lemon-yellow*: sulphur, orpiment. — 6. *Ocher-yellow*: yellow, with brown; yellow ochre. — 7. *Wine-yellow*: topaz and fluorite. — 8. *Cream-yellow*: some varieties of kaolinite. — 9. *Orange-yellow*: orpiment.

G. RED. 1. *Aurora-red*: red, with much yellow; some realgar. — 2. *Hyacinth-red*: red, with yellow and some brown; hyacinth garnet. — 3. *Brick-red*: polyhalite, some jasper. — 4. *Scarlet-red*: bright red, with a tinge of yellow; cinnabar. — 5. *Blood-red*: dark red, with some yellow; pyrope. — 6. *Flesh-red*: feldspar. — 7. *Carmine-red*: pure red; ruby sapphire. — 8. *Rose-red*: rose quartz. — 9. *Crimson-red*: ruby. — 10. *Peachblossom-red*: red, with white and gray; lepidolite. — 11. *Columbine-red*: deep red, with some blue; garnet. — 12. *Cherry-red*: dark red, with some blue and brown; spinel, some jasper. — 13. *Brownish-red*: jasper, limonite.

H. BROWN. 1. *Reddish brown*: garnet, zircon. — 2. *Clove-brown*: brown, with red and some blue; axinite. — 3. *Hair-brown*: wood-opal. — 4. *Broccoli-brown*: brown, with blue, red, and gray; zircon. — 5. *Chestnut-brown*: pure brown. — 6. *Yellowish brown*: jasper. — 7. *Pinchbeck-brown*: yellowish brown, with a metallic or metallic-pearly luster; several varieties of talc, bronzite. — 8. *Wood-brown*: color of old wood nearly rotten; some

specimens of asbestos. — 9. *Liver-brown*: brown, with some gray and green; jasper. — 10. *Blackish brown*: bituminous coal, brown coal.

### 3. LUSTER

**363. Nature of Luster.** — The luster of minerals varies with the nature of their surfaces. A variation in the quantity of light reflected produces different degrees of intensity of luster; a variation in the nature of the reflecting surface produces different kinds of luster.

**364. Kinds of Luster.** — The kinds of luster recognized are as follows:

1. **METALLIC**: the luster of the metals, as of gold, copper, iron, tin.

In general, a mineral is not said to have metallic luster unless it is opaque in the mineralogical sense, that is, it transmits no light on the edges of thin splinters. Some minerals have varieties with metallic and others with non-metallic luster; this is true of hematite.

Imperfect metallic luster is expressed by the term *sub-metallic*, as illustrated by columbite, wolframite. Other kinds of luster are described briefly as **NON-METALLIC**.

2. **NON-METALLIC**. *A. Adamantine*: the luster of the diamond. When also sub-metallic, it is termed *metallic-adamantine*, as cerussite, pyrrargyrite.

Adamantine luster belongs to substances of high refractive index. This may be connected with their relatively great density (and hardness), as with the diamond, also corundum, etc.; or because they contain heavy molecules, thus most compounds of lead, not metallic in luster, have a high refractive index and an adamantine luster.

*B. Vitreous*: the luster of broken glass. An imperfectly vitreous luster is termed *sub-vitreous*. The vitreous and sub-vitreous lusters are the most common in the mineral kingdom. Quartz possesses the former in an eminent degree; calcite, often the latter.

*C. Resinous*: luster of the yellow resins, as opal, and some yellow varieties of sphalerite.

*D. Greasy*: luster of oily glass. This is near resinous luster, but is often quite distinct, as nephelite.

*E. Pearly*: like pearl, as talc, brucite, stilbite, etc. When united with sub-metallic, as in hypersthene, the term *metallic-pearly* is used.

Pearly luster belongs to the light reflected from a pile of thin glass-plates; similarly it is exhibited by minerals, which, having a perfect cleavage, may be partially separated into successive plates, as on the basal plane of apophyllite. It is also shown for a like reason by foliated minerals, as talc and brucite.

*F. Silky*: like silk; it is the result of a fibrous structure. Ex. fibrous calcite, fibrous gypsum.

The different degrees and kinds of luster are often exhibited differently by unlike faces of the same crystal, but always similarly by like faces. For example, the basal plane of apophyllite has a pearly luster wanting in the prismatic faces, which have a vitreous luster.

As shown by Haidinger, only vitreous, adamantine, and metallic luster belong to faces perfectly smooth and pure. In the first, the refractive index of the mineral is 1.3–1.8; in the second, 1.9–2.5; in the third, about 2.5. The true difference between metallic and vitreous luster is due to the effect which the different surfaces have upon the reflected light; in general, the luster is produced by the union of two simultaneous impressions made upon the eye. If the light reflected from a metallic surface be examined by a nicol prism (or the dichroscope of Haidinger, Art. 393), it will be found that both rays, that vibrating in the plane of incidence and that whose vibrations are normal to it, are alike, each having the

color of the material, only differing a little in brilliancy; on the contrary, of the light reflected by a vitreous substance, those rays whose vibrations are at right angles to the plane of incidence are more or less polarized, and are colorless, while those whose vibrations are in this plane, having penetrated somewhat into the medium and suffered some absorption, show the color of the substance itself. A plate of red glass thus examined will show a colorless and a red image. Adamantine luster occupies a position between the others.

**365. Degrees of Luster.** — The *degrees of intensity* of luster are classified as follows:

1. *Splendent*: reflecting with brilliancy and giving well-defined images, as hematite, cassiterite.

2. *Shining*: producing an image by reflection, but not one well-defined, as celestite.

3. *Glistening*: affording a general reflection from the surface, but no image, as talc, chalcopyrite.

4. *Glimmering*: affording imperfect reflection, and apparently from points over the surface, as flint, chaledony.

A mineral is said to be *dull* when there is a total absence of luster, as chalk, the ochers, kaolin.

**366. Play of Colors. Opalescence. Iridescence.** — The term *play of colors* is used to describe the appearance of several prismatic colors in rapid succession on turning the mineral. This property belongs in perfection to the diamond, in which it is due to its high dispersive power. It is also observed in precious opal, where it is explained on the principle of interference; in this case it is most brilliant by candle-light.

The expression *change of colors* is used when each particular color appears to pervade a larger space than in the play of colors and the succession produced by turning the mineral is less rapid. This is shown in labradorite, as explained under that species.

*Opalescence* is a milky or pearly reflection from the interior of a specimen. Observed in some opal, and in cat's-eye.

*Iridescence* means the exhibition of prismatic colors in the interior or on the surface of a mineral. The phenomena of the play of colors, iridescence, etc., are sometimes to be explained by the presence of minute foreign crystals, in parallel positions; more generally, however, they are caused by the presence of fine cleavage-lamellæ, in the light reflected from which interference takes place, analogous to the well-known Newton's rings (see Art. 336).

**367. Tarnish.** — A metallic surface is tarnished when its color differs from that obtained by fracture, as is the case with specimens of bornite. A surface possesses the *steel tarnish* when it presents the superficial blue color of tempered steel, as columbite. The tarnish is *irised* when it exhibits fixed prismatic colors, as is common with the hematite of Elba. These tarnish and iris colors of minerals are owing to a thin surface or film, proceeding from different sources, either from a change in the surface of the mineral or from foreign incrustation; hydrated iron oxide is one of the most common sources of it and produces the colors on anthracite and hematite.

**368. Asterism.** — This name is given to the peculiar star-like rays of light observed in certain directions in some minerals. This is seen by reflected light in the form of a six-rayed star in sapphire, and is also well shown by transmitted light (as of a small flame) with the phlogopite mica from South Burgess, Canada. In the former case it is explained by the presence of thin twinning-lamellæ symmetrically arranged. In the other case it is due to the presence of minute inclosed crystals, also symmetrically arranged, which are probably rutile or tourmaline in most cases. Crystalline faces which have

been artificially etched also sometimes exhibit asterism. The peculiar light-figures sometimes observed in reflected light on the faces of crystals, either natural or etched, are of similar nature.

**369. Schillerization.** — The general term *schiller* is applied to the peculiar luster, sometimes nearly metallic, observed in definite directions in certain minerals, as conspicuously in schiller-spar (an altered variety of bronzite), also in diallage, hypersthene, sunstone, and others. It is explained by the reflection either from minute inclosed plates in parallel position or from the surfaces of minute cavities (negative crystals) having a common orientation. In many cases it is due to alteration which has developed these bodies (or the cavities) in the direction of solution-planes (see Art. 286). The process by which it has been produced is then called *schillerization*.

**370. Fluorescence.** — The emission of light from within a substance while it is being exposed to direct radiation, or in certain cases to an electrical discharge in a vacuum tube, is called *fluorescence*. It is best exhibited by fluorite, from which the phenomenon gained its name. Thus, if a beam of white light be passed through a cube of colorless fluorite a delicate violet color is called out in its path. This effect is chiefly due to the action of the ultra-violet rays, and is connected with a change of refrangibility in the transmitted light.

The electrical discharge from the negative pole of a vacuum tube calls out a brilliant fluorescence not only with the diamond, the ruby, and many gems, but also with calcite and other minerals. Such substances may continue to emit light, or *phosphoresce*, after the discharge ceases.

**371. Phosphorescence.** — The *continued* emission of light by a substance (not incandescent) produced especially after heating, exposure to light or to an electrical discharge, is called *phosphorescence*.

Fluorite becomes highly phosphorescent after being heated to about 150° C. Different varieties give off light of different colors; the *chlorophane* variety, an emerald-green light; others purple, blue, and reddish tints. This phosphorescence may be observed in a dark place by subjecting the pulverized mineral to a heat below redness. It may even be produced by a sharp blow with a hammer. Some varieties of white limestone or marble, after slight heating, emit a yellow light; so also tremolite, danburite, and other species.

The X-ray and ultra-violet light will produce phosphorescence in willemite, kunzite, and some diamonds. The fact that willemite glows when exposed to ultra-violet light is made use of in testing the residues from a willemite ore to make certain the separation has been complete. Radium emanations cause certain minerals to phosphoresce, as willemite and wurtzite.

Exposure to the light of the sun produces very apparent phosphorescence with many diamonds, but some specimens seem to be destitute of this power. This property is most striking after exposure to the blue rays of the spectrum, while in the red rays it is rapidly lost. A mixture of calcium sulphide and bismuth will phosphoresce for a considerable period after being exposed to sunlight.

## SPECIAL OPTICAL CHARACTERS BELONGING TO CRYSTALS OF THE DIFFERENT SYSTEMS

**372.** All crystallized minerals may be grouped into three grand classes, which are distinguished by their physical properties, as well as their geometrical form. These three classes are as follows:

A. *Isometric class*, embracing crystals of the isometric system, which are referred to three equal rectangular axes.

B. *Isodiametric class*, embracing crystals of the tetragonal and hexagonal systems, referred to two, or three, equal horizontal axes and a third, or fourth, axis unequal to them at right angles to their plane. Crystals of this class have a fixed principal axis of crystallographic symmetry.

C. *Anisometric class*, embracing the crystals of the orthorhombic, monoclinic, and triclinic systems, referred to three unequal axes. Crystals of this class are without a fixed axis of crystallographic symmetry.

**373. Isotropic Crystals.** — Of the three classes, the ISOMETRIC CLASS includes all crystals which, with respect to light and related phenomena involving the ether, are *isotropic* (from the Greek, signifying *equal turning*); that is, those which have like optical properties in all directions. Their distinguishing characteristic is that light travels through them with equal velocity in all directions, provided their molecular equilibrium is not disturbed by external pressure or internal strain. If it be imagined therefore that light starts from a point within an isotropic medium at a given moment of time the resulting wave surface will be a sphere.

It must be emphasized here, however, that such a crystal is *not* isotropic with reference to those characters which depend directly upon the molecular structure alone, as cohesion and elasticity. (See Art. 275.)

Further, amorphous bodies, as glass and opal, which are destitute of any orientated molecular structure — that is, those in which all directions are sensibly the same — are also isotropic, and not only with reference to light, but also as regards their strictly molecular properties.

**374. Anisotropic Crystals; Uniaxial and Biaxial.** — Crystals of the ISODIAMETRIC and ANISOMETRIC CLASSES, on the other hand, are in distinction *anisotropic* (from the Greek, signifying *unequal turning*). Their optical properties are in general unlike in different directions, or, more particularly, the velocity with which light is propagated varies with the direction.

Further, in crystals of the isodiametric class that variable property of the light-ether upon which the velocity of propagation depends remains constant for all directions which are normal to, or, again, for all those equally inclined to, the vertical crystallographic axis. In the direction of this axis there is no double refraction; it is hence called the *optic axis*, and the crystals of this class are said to be *uniaxial*.

Crystals of the third or anisometric class have more complex optical relations requiring special explanation, but in general it may be stated that in them there are always two directions analogous in character to the single optic axis spoken of above; hence, these crystals are said to be optically *biaxial*.

#### A. ISOMETRIC CRYSTALS

**375.** It has been stated that crystals of the isometric system are optically *isotropic*, and hence light travels with the same velocity in every direction in them. Light can, therefore, suffer only single refraction in passing into an isotropic medium; or, in other words, there can be but one value of the refractive index for a given wave-length. If this be represented by  $n$ , while  $V$  is the velocity of light in air and  $v$  that in the given medium, then

$$n = \frac{V}{v}, \quad \text{or} \quad v = \frac{V}{n}.$$

The wave-front for light-waves propagated from any point within such an isotropic medium is, as already stated, a sphere. The sphere, therefore, may be taken to represent the optical properties of an isotropic medium. Sections of a sphere normal to any diameter will always be circles. These circular sections with like radii in all directions correspond to the fact that the optical character of an isotropic substance is the same in all directions normal to the line of light propagation. Or, in other words, light vibrations may take place in any direction normal to the direction of transmission; *i.e.*, the light is not polarized. Further its velocity remains uniform no matter what may be the direction of its vibration.

This statement holds true of all the classes of isometric crystals. In other words, a crystal of maximum symmetry, as fluorite, and one having the restricted symmetry characteristic of the tetrahedral or pyritohedral divisions, have alike the same isotropic character. Two of the classes, however, namely, the plagiohedral and the tetartohedral classes, differ in this particular: that crystals belonging to them may exhibit what has already been defined (Art. 350) as circular polarization.

**376. Behavior of Sections of Isometric Crystals in Polarized Light.** — In consequence of their isotropic character, isometric crystals exhibit no special phenomena in polarized light. As a section of an isotropic substance (isometric crystal or some amorphous material) has no polarizing or doubly refracting effect upon light it does not change at all the character of light that enters it from the polarizer of a polariscope. Therefore thin sections of isotropic media when examined in a polariscope or polarizing microscope with the nicols crossed will appear dark in all positions. In other words, they are always extinguished. Further, when a colored mineral is examined without the analyzer there will be no change in its color when the section is revolved with the stage of the microscope. Some anomalies are mentioned on a later page, (Art. 429).

The single refractive index of an isotropic substance may be determined by means of a prism (see Art. 327) with its edge cut in any direction whatever.

## B. UNIAXIAL CRYSTALS

### *General Optical Relations*

**377.** The crystallographic and optical relations of crystals belonging to crystals of the tetragonal and hexagonal systems have already been briefly summarized (Art. 374); it now remains to develop their optical characters more fully. This can be done most simply by making frequent use of the familiar conception of a light-ray to represent the character and motion of the light-wave.

**378. Behavior of Light in Uniaxial Minerals.** — Light entering a uniaxial mineral is in general broken up into two rays which are polarized in planes perpendicular to each other and which travel with different velocities and therefore have different indices of refraction. One of the two rays derived from a single incident ray always vibrates in the plane of the horizontal crystallographic axes. The other ray vibrates at right angles to the first and always in a vertical plane that includes the vertical crystallographic axis. The optical character of a uniaxial mineral is uniform for all directions lying in the horizontal crystallographic plane and therefore the ray whose vibrations lie in this plane will have uniform velocity no matter what its direction

of transmission. This ray will therefore have a single and constant index of refraction, commonly designated by  $\omega$ . Since this ray follows the usual law as to the constant ratio between the sines of the angles of incidence and refraction and in general behaves in an ordinary way it is called the *ordinary ray*. The ray which vibrates in a plane that includes the vertical crystallographic axis will have the direction of its vibration constantly changing as the direction of its path through the crystal changes and its velocity will correspondingly vary. Its index of refraction will therefore depend upon the direction of its propagation and it will not in general obey the usual sine law. This ray is therefore called the *extraordinary ray*.

When light travels in a uniaxial mineral in a direction parallel to the vertical crystallographic axis, since all its vibrations must take place in the horizontal plane, it behaves wholly as the ordinary ray with a single velocity and refractive index. There can be no double refraction of light, therefore, along this direction and in this case the mineral will behave like an isotropic substance. This direction of no double refraction, coincident with the vertical crystal axis, is known as the *optic axis* and as there is only one such direction in this optical group the latter is called *uniaxial*. As soon as the direction of transmission becomes inclined to the vertical crystal axis the light is doubly refracted and as the inclination increases the direction of vibration of the light of the extraordinary ray departs more and more from the plane of vibration of the ordinary ray with a corresponding change in its velocity and refractive index. The difference between the refractive indices of the two rays becomes a maximum when the light passes through the mineral in a horizontal direction with the direction of vibration of the extraordinary ray parallel to the vertical crystal axis — or in other words as divergent as possible from the horizontal plane. The value of the refractive index of the extraordinary ray when at its maximum difference from the constant index of the ordinary ray is the one always quoted and is indicated by  $\epsilon$ . These two indices,  $\omega$  and  $\epsilon$ , are called the *principal indices* of a uniaxial crystal. A *principal section* of a uniaxial crystal is a section passing through the vertical axis.

**379. Positive and Negative Crystals.** — Uniaxial crystals are divided into two classes, depending upon whether the velocity of the extraordinary ray is greater or less than that of the ordinary ray. Those in which the refractive index of the ordinary ray,  $\omega$ , is less than that of the extraordinary ray,  $\epsilon$  ( $\omega < \epsilon$ ), are called *positive*. This is illustrated by quartz for which (for yellow sodium light):

$$\omega = 1.544. \qquad \epsilon = 1.553.$$

On the other hand, if  $\epsilon$  is less than  $\omega$  ( $\epsilon < \omega$ ), the crystal is said to be *negative*.\* Calcite is an example for which (for sodium light)

$$\omega = 1.658. \qquad \epsilon = 1.486.$$

Other examples are given later (Art. 383).

**380. Determination of the Refractive Indices in Uniaxial Crystals.** — The indices of refraction of uniaxial minerals are measured in much the same

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\* It will assist in remembering these relations to note that the first vowel in the words positive and negative agrees with the symbol used for the smaller index of refraction in each case.

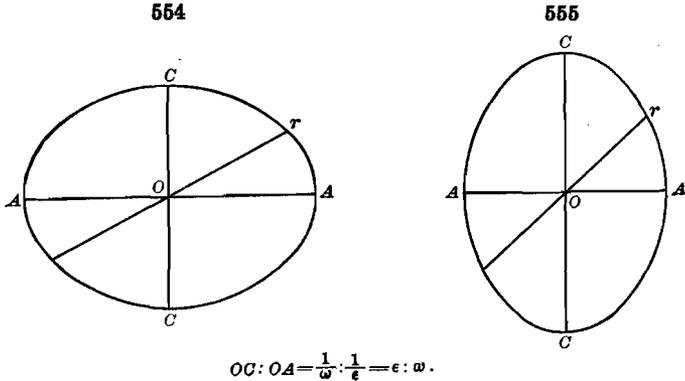
way as in the case of isotropic substances. With uniaxial crystals, however, the prism or plate used must have a definite crystallographic orientation. If a prism is employed its edge should be parallel to the optic axis, or in other words parallel to the vertical crystal axis of the mineral. When such a prism is examined on the refractometer two refracted rays are seen, the angles of refraction of which can be measured by either the method of minimum deviation or perpendicular incidence as described in Art. 327. The two rays are polarized, the ordinary ray vibrating in the horizontal plane and the extraordinary ray vibrating in the vertical plane, *i.e.*, parallel to the edge of the prism. The plane of vibration of each ray must be determined by the use of a nicol prism held in front of the eyepiece of the refractometer. When the plane of the nicol is horizontal the image belonging to the ordinary ray will be visible and when the plane of the nicol is vertical only that of the extraordinary ray will appear. In this way the indices of the two rays are determined and the positive or negative character of the mineral is established. It is possible to obtain these measurements in prisms with different crystallographic orientation but the difficulties attending their preparation are so great that such prisms are very seldom used.

If the method of total reflection is used a single plate will suffice, provided it lies either in the prism zone of the crystal, or is parallel to the basal plane. In each case two shadows will be observed, corresponding in their position to the angles of total reflection of the two rays. When the plate is cut parallel to a face in the prism zone one of these shadows, that belonging to the ordinary ray, will remain stationary as the plate is revolved on the hemisphere of the total refractometer while the shadow of the extraordinary ray will vary from being coincident with that of the ordinary ray to a certain maximum divergence from that position. This maximum difference in position, which may yield a greater or less angle than that of the ordinary ray, depending upon the optical character of the mineral, is the angle corresponding to the true value of the refractive index of the extraordinary ray. There will be two positions at  $180^\circ$  apart during the complete revolution of the section at which this value may be measured. If the plate was cut parallel to the basal plane of the crystal the two shadows would both be stationary during such a revolution and the value of the angle for both rays can be measured in any position of the plate.

**381. Wave-surface.** — Remembering that the velocity of light-propagation is always inversely proportional to the corresponding refractive index, it is obvious that the velocity of the ordinary ray for all directions in a uniaxial crystal must be the same, being uniformly proportional to  $\frac{1}{\omega}$ . In other words, supposing light originates at a point within a uniaxial crystal the ordinary ray would travel out in all directions with uniform velocity and its wave-front would form a sphere.

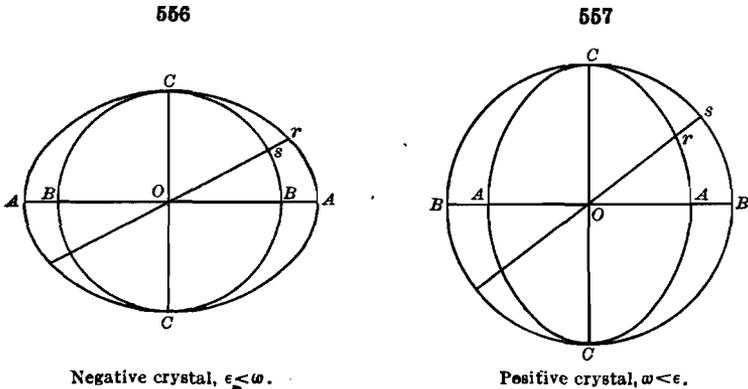
For the extraordinary ray, however, the velocity varies with the direction, being proportional to  $\frac{1}{\epsilon}$  in a horizontal direction and becoming sensibly equal to  $\frac{1}{\omega}$  when nearly coincident with the direction of the vertical axis. The law of the varying change of velocity between these values,  $\frac{1}{\omega}$  and  $\frac{1}{\epsilon}$ , is given

by an ellipse whose axes ( $OC, OA$ , Figs. 554, 555) are respectively proportional to the above values.



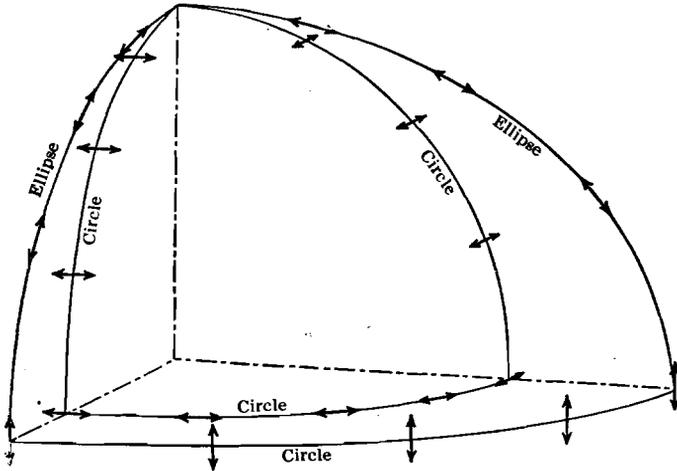
The wave-front of the extraordinary ray is then a spheroid, or an ellipsoid of revolution whose axis coincides with the vertical crystallographic axis, that is, the optic axis. In the direction of the vertical axis it is obvious that the wave-fronts of the ordinary and extraordinary rays will coincide.

Figures 556 and 557 represent vertical sections of the combined wave-



surfaces for both rays. Fig. 556 gives that for a *negative* crystal like calcite ( $\epsilon < \omega$ ), the ellipsoidal wave surface of the extraordinary ray being outside the spherical surface of the ordinary ray; Fig. 557 that of a *positive* crystal like quartz ( $\omega < \epsilon$ ) with the ellipsoidal surface within that of the sphere. Fig. 558 is an attempt to show the relations of the two wave-fronts of a negative crystal in perspective for a single octant. The constant value of the velocity of the ordinary ray ( $\frac{1}{\omega}$ ), whatever its direction in the plane of Figs. 556 and 557, is expressed by the radius of the circle ( $= OC$ ). On the other hand, the velocity of the extraordinary ray in the horizontal direction is given by  $OA$  ( $\frac{1}{\epsilon}$ ), while in any oblique direction, as  $Osr$ , Fig. 556 ( $Ors$ , Fig. 557), it is

558



expressed by the length of this line, becoming more and more nearly equal to  $OC \left(\frac{1}{\omega}\right)$  as its direction approaches that of the vertical axis.

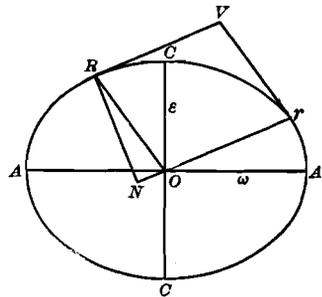
**382. Uniaxial Indicatrix.** — The optical structure of a uniaxial crystal can be represented by an ellipsoid of revolution, called the *Indicatrix*,\* from which can be obtained the directions of vibration and indices of refraction of the ordinary and extraordinary rays derived from any single incident ray. Fig. 559 represents a principal section of such an ellipsoid for an optically negative crystal, the line *C-C* being its axis of revolution. The axes of this ellipsoid are made inversely proportional to the indices of refraction of the two rays,  $\omega$  and  $\epsilon$ , as follows:

$$OC : OA = \frac{1}{\omega} : \frac{1}{\epsilon} \text{ or } \epsilon : \omega.$$

In this figure let *Or* be a direction of transmission of light. Let *Vr* and *VR* be tangents to the elliptical surface at the points *r* and *R* and *OR* be a radius vector parallel to the tangent *Vr*. *Or* and *OR* form then what are known as *conjugate radii*. From the geometrical properties of an ellipse it follows that the area of any parallelogram with conjugate radii forming two sides, such as *ORVr* in Fig. 559, is constant and equal to the area of a parallelogram having *OC* and *OA* as two sides. Let *RN* be perpendicular to the extended line *Or*. Then the area of *ORVr* will be equal to *RN·Or*. It follows since *RN·Or* = *OA·OC* = a constant, *k*, that

$$Or = \frac{OA \cdot OC}{RN} = \frac{k}{RN}; \text{ also } OA = \frac{k}{OC}$$

559



\* The Optical Indicatrix and the Transmission of Light in Crystals, by L. Fletcher, London, 1892.

From the last expression we see that  $OA$  and  $OC$  are inversely proportional to each other, or, in other words, as  $OC$  represents the minimum index,  $OA$  will represent the corresponding velocity of light which will be the maximum for any transmission direction in the crystal. In the same way  $Or$  and  $RN$  are inversely proportional to each other, the distance  $Or$  representing the velocity of the extraordinary ray traveling along that direction while  $RN$  will represent its refractive index. The line  $RN$  will also give the direction of vibration of the extraordinary ray.

For the radius vector  $Or$  there will be another possible direction perpendicular to it and also normal to the ellipsoidal surface. This will be a line from  $O$  perpendicular to the principal section represented in Fig. 559. This line will lie in the horizontal circular section of the indicatrix ellipsoid with its length equal to  $OA$  which in turn is proportional to the index of the ordinary ray,  $\omega$ . So for a given direction of transmission of light, such as  $Or$ , the two lines that are perpendicular to it and at the same time normal to the surface of the indicatrix yield both the indices of refraction of the two rays and the directions of their vibrations.

If, however, the light is passing parallel to the principal axis of the indicatrix, *i.e.*,  $C-C$ , Fig. 559, there will be an infinite number of lines which are perpendicular to this direction and at the same time normal to the surface of the indicatrix. These will lie in the horizontal circular section of the ellipsoid and consequently will be of a uniform length. From this it is evident that such a transmitted ray may vibrate in any transverse direction and will possess a single index of refraction and velocity. Along this direction, known as the optic axis, there will consequently be no double refraction of the light.

**383. Examples of Positive and Negative Crystals.** — The following lists give prominent positive and negative uniaxial crystals, with the values of the refractive indices,  $\omega$  and  $\epsilon$ , for each, corresponding to yellow sodium light.\* The difference between these,  $\omega - \epsilon$  or  $\epsilon - \omega$ , is also given; this measures the birefringence or *strength* of the double refraction.

It may be remarked that in some species both + and - varieties have been observed. Certain crystals of apophyllite are positive for one end of the spectrum and negative for the other, and consequently for some color between the two extremes it has no double refraction. The same is true for some other species (*e.g.*, chabazite) of weak double refraction.

## NEGATIVE CRYSTALS

	$\omega$	$\epsilon$	$\omega - \epsilon$
Proustite.....	2.979	2.711	0.268
Calcite.....	1.658	1.486	0.172
Tourmaline.....	1.638	1.620	0.018
Corundum.....	1.768	1.760	0.008
Beryl.....	1.584	1.578	0.006
Vesuvianite.....	1.720	1.715	0.005
Nephelite.....	1.542	1.538	0.004
Apatite.....	1.634	1.631	0.003

## POSITIVE CRYSTALS

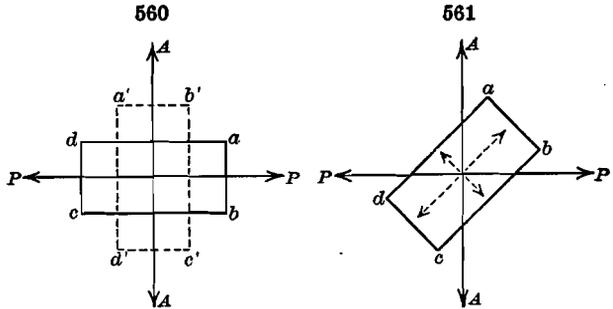
	$\omega$	$\epsilon$	$\epsilon - \omega$
Rutile.....	2.616	2.903	0.287
Cassiterite.....	1.997	2.093	0.096
Zircon.....	1.923	1.968	0.045
Brucite.....	1.559	1.580	0.021
Phenacite.....	1.654	1.670	0.016
Quartz.....	1.544	1.553	0.009
Apophyllite.....	1.535	1.533	0.002
Leucite.....	1.508	1.509	0.001

\* From tables by E. S. Larsen.

*Examination of Uniaxial Crystals in Polarized Light*

**384. Section Normal to the Axis in Parallel Polarized Light.** — Suppose a section of a uniaxial crystal to be cut perpendicular to the vertical crystallographic axis. It has already been shown that light passing through the crystal in this direction suffers no double refraction; consequently, such a section examined in *parallel* polarized light behaves as a section of an isotropic substance. If the nicols are crossed it appears *dark*, or *extinguished*, and remains so when revolved.

**385. Section Parallel to the Axis.** — A section cut parallel to the vertical axis, as already explained, has two directions of light-vibration, one parallel to this axis, that of the extraordinary ray, and the other at right angles to it, that of the ordinary ray. A ray of light falling upon such a section with perpendicular incidence is divided into the two rays, ordinary and extraordinary, which travel on in the same path through the crystal, but one of them retarded relatively to the other. When such a section is examined in polarized light with crossed nicols it will appear dark, or be extinguished, when its vibration directions lie parallel to the vibration directions of the nicols. Assume that the section *abcd*, Fig. 560, lies with the direction of its vertical crystallographic axis parallel to *P-P*, which represents the vibration direction of the polarizer. The light entering the section under these conditions will be vibrating parallel to the vertical axis of the crystal and will therefore pass into the mineral wholly as the extraordinary ray, there being no vibration possible in the direction of the ordinary ray. The light will, therefore, leave the section with the same direction of vibration as when it entered and will be entirely lost by reflection in the analyzer. If the section is turned at an angle of 90°, as *a'b'c'd'*, Fig. 560, similar conditions



prevail, although in this case the light will vibrate in the section as the ordinary ray. Therefore in such a section there will be four positions during its complete revolution on the stage of the polariscope or microscope when it will be extinguished.

If the section stand obliquely, as *abcd* in Fig. 561, it will appear light to the eye (and usually colored), for the vibrations parallel to *P-P* that have passed through the polarizer have upon resolution a component in the direction of each of the vibration-planes of the section. Again, each of these components can be resolved along the direction of the vibration-plane of the upper nicol, *A-A*. Therefore, two rays will emerge from the analyzer, both having the same vibration-plane, but one more or less retarded with reference to the other, the amount of retardation increasing with the birefringence and the thickness of the section. In general, therefore, these rays will interfere, and if the thickness of the section is sufficient (and not too great) it will appear colored in white light and, supposing the thickness uniform, of the same color throughout.

**386. Parallel Extinction.** — When the vibration directions of a section coincide with those of the polarizer and analyzer, assuming them to be crossed, the section appears dark and it is said to be in the position of extinction. If a section extinguishes when its crystallographic axis or axial plane is parallel to one of the planes of vibration of the nicols it is said to show *parallel extinction*. If, on the other hand, no such parallelism exists between the crystallographic directions and the directions of vibration in the mineral the section is said to show *inclined extinction*.

In the case of uniaxial minerals, since the vibration directions always lie in some crystallographic axial plane, all sections of such minerals will show parallel extinction.

**387. Determination of the Relative Character of the Extinction Directions of a Given Uniaxial Mineral.** — The relative characters of the extinction directions of a section of a uniaxial mineral are to be determined by the use of the quartz wedge or the sensitive tint as described in Art.

**348.** If the orientation of the section is known so that it can be told which of the directions of vibration belongs to the ordinary and which to the extraordinary ray the positive or negative character of the mineral can be determined. For instance, if the ordinary ray is proved to be the faster of the two (*i.e.*, the *X* direction) it follows that its index is the smaller, *i.e.*,  $\omega < \epsilon$ , and the mineral is positive.

**388. Interference Colors of Uniaxial Minerals. Birefringence.** — The interference color of any section of a uniaxial mineral depends upon the following: first upon the thickness of the section, second upon the strength of the double refraction of the mineral, *i.e.*, its birefringence, this being measured by the difference between the indices of refraction of the two rays in the section, and third upon the crystallographic orientation of the section. A section cut parallel to the basal plane shows no double refraction and therefore cannot exhibit any interference color. The strength of the birefringence, the other conditions remaining uniform, increases as the inclination of the section to the basal plane increases. The highest birefringence of a given mineral is therefore shown by its prismatic sections.

The following table \* gives the thickness (in millimeters) of sections of a few uniaxial crystals which yield *red* of the first order:

	Birefringence ( $\omega - \epsilon$ ) or ( $\epsilon - \omega$ )	Thickness in Millimeters
Rutile.....	0.287	0.0019
Calcite.....	0.172	0.0032
Zircon.....	0.062	0.0089
Tourmaline.....	0.023	0.0240
Quartz.....	0.009	0.0612
Nephelite.....	0.004	0.1377
Leucite.....	0.001	0.5510

Again, as another example, it may be noted that with zircon ( $\epsilon - \omega = 0.062$ ), a thickness of about 0.009 mm. gives red of the first order; of 0.017 red of the second order; of 0.026 red of the third order.

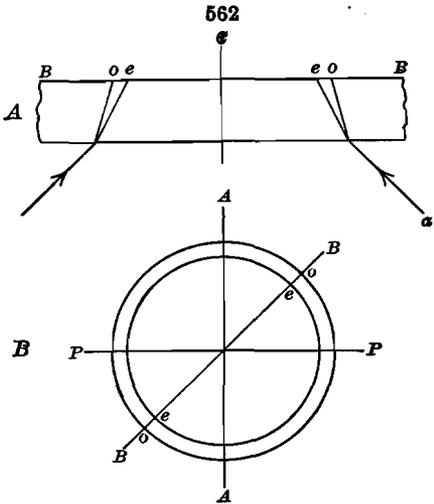
The methods ordinarily used to determine the birefringence of a section (not  $\perp c$  axis) of a uniaxial crystal, as also to fix the relative value of its two vibration-directions, have already been discussed, see Arts. 347 and 348.

**389. Effects of Convergent Polarized Light upon Sections of Uniaxial Minerals. Uniaxial Interference Figures.** — When certain sections of uni-

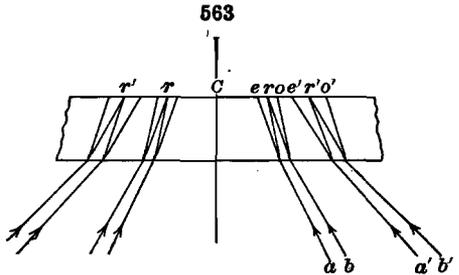
\* See further, Rosenbusch (Mikr. Phys. Min., 1904, p. 292), from whom these are taken.

axial minerals are observed in convergent polarized light they show what are known as *interference figures*. A symmetrical interference figure is obtained in uniaxial minerals by allowing converging polarized light to pass through a basal section of the crystal. Parallel polarized light entering such a section would suffer no double refraction and consequently give no interference. To convert the parallel polarized light that comes from the polarizer into convergent light a lens is placed between the polarizer and the section. Under these conditions a sharply converging cone of light rays enters the section. Another lens is placed above the section to change these oblique rays back again into a parallel position. Such an instrument is known as a *conoscope* and may be obtained by placing a pair of lenses between the polarizer and analyzer of a polariscope, or, in case the polarizing microscope is used, the small converging lens that lies above the polarizer is swung into position by a lever and at the same time a small lens known as the Bertrand lens is introduced into the microscope tube.

Under such conditions the light entering the section is composed of a

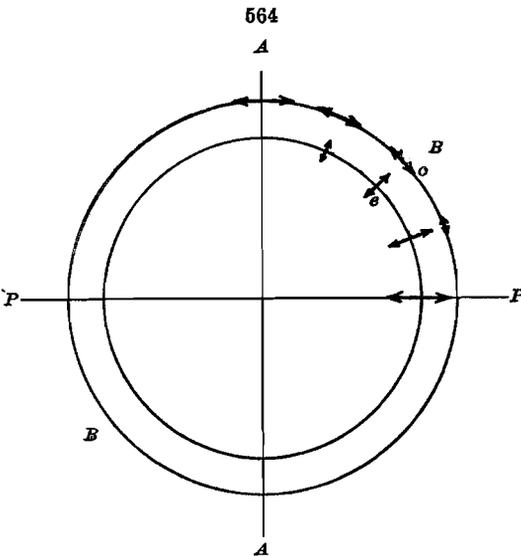


converging system of rays polarized and vibrating in the plane  $P-P$ , Fig. 562. Let  $B-B$  (Fig. 562, A) be a vertical cross section of the mineral section along the line  $B-B$ , Fig. 562, B. Consider any ray, as  $a$ , entering the section. Since the ray enters the section obliquely it will be doubly refracted into the rays  $o$  and  $e$ .



The mineral being taken as calcite the extraordinary ray (calcite being negative) will have the greater velocity and be least refracted. As the light enters the section in the form of a cone the traces of the two rays as they emerge from the section will be circles, Fig. 562, B. Now consider in a similar case the action of the two rays  $a$  and  $b$  or  $a'$  and  $b'$  (Fig. 563) upon each other. Ray  $a$  on entering the section is doubly refracted and polarized into the rays  $e$  and  $o$  which are considered as emerging from the section at the points  $e$  and  $r$ . Ray  $b$  also on entering the section is doubly refracted and polarized. Suppose the extraordinary ray derived from  $b$  emerges from the section at the same point as the ordinary ray derived from  $a$ , that is at  $r$ . Since it travels with a greater velocity the extraordinary ray emerging at this point will have advanced in its phase over that of the ordinary ray. In that case they would be in a condition to interfere with each other except that they are vibrating in planes perpendicular to each other and so cannot. The two rays travel on, vibrating in planes at right angles to each other and maintaining

this difference in phase until they reach the upper nicol; there they are each resolved into rays vibrating in the plane  $A-A$ , Fig. 562,  $B$ , and are now in condition to interfere with each other. Let it be assumed that the conditions are right for the extraordinary ray to emerge from the section just one wavelength ahead of the ordinary ray. Their components in the upper nicol will have opposite phases and therefore compensate each other, see Art. 335. If the section is viewed in a monochromatic light (for instance, sodium light) this interference will result in a black point. But as these rays are converging in the form of a cone they will make, when they strike the section, a circular trace upon its surface and their interference will result in a dark ring. Going out from the center of the section there will be a succession of these rings corresponding to the interference of waves 1, 2, 3, 4, 5, etc., wave-lengths apart. As the distance from the center of the section is increased, the paths



of the refracted rays in the section are lengthened and the points of interference are brought closer together. This will cause the interference rings to lie nearer together as the distance from the center of the figure increases.

Fig. 564 is a top view of the section without taking into consideration the effects of the upper nicol. Let the two circles represent the traces of the emergence of the two rays  $e$  and  $o$  into which one incident conical ray is divided;  $e$ , being the least refracted (for calcite), will be the inner one. The plane of vibration of  $e$

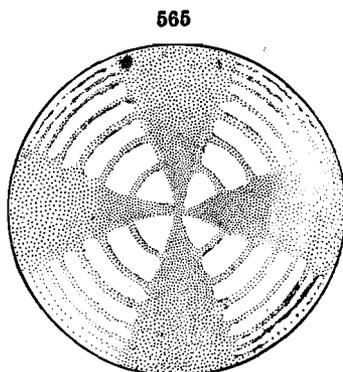
is always parallel to some plane passing through the vertical axis of the crystal, therefore the trace of its plane of vibration upon the surface of the section will always be in a radial direction. The plane of vibration of  $o$  is at right angles to that of the extraordinary ray and parallel to the horizontal axes of the crystal, therefore the trace of its plane of vibration upon the surface of the section will always be in a tangential direction, see Fig. 564. Along the line  $P-P$ , Fig. 564, only light vibrating in a radial plane or that of the extraordinary ray can come through the section, since the light entering the section cannot be resolved into the vibrations of the ordinary ray. The intensity and direction of vibration of the light that emerges from the section along the line  $P-P$  is represented by the double arrow on that line. Along the line  $A-A$ , since the light entering the section is still vibrating in the plane  $P-P$ , all the light passing through the section must vibrate as the ordinary ray. It is evident, therefore, that along these two directions,  $P-P$  and  $A-A$  the plane of vibration of the light is not changed by passage through the section and consequently such light will be completely absorbed in the

upper nicol. In this way dark brushes will be formed along the lines  $P-P$  and  $A-A$ . A dark spot will also be formed in the center of the field because any light entering the section at this point must enter in the direction of the optic axis and therefore will not be doubly refracted and consequently will also be absorbed in the analyzer.

Now consider point  $B$ , Fig. 564, which lies  $45^\circ$  away from  $P$  and  $A$ . Here the directions of vibration of  $e$  and  $o$  would be equally inclined to the planes of vibration of the polariscope,  $A-A$  and  $P-P$ . Light striking the section at  $B$  would be vibrating in the plane  $P-P$  but by resolution a component vibrating in the direction  $B-B$  would come through the section as the ray  $e$ ; in the same manner a component vibrating in a direction at right angles to  $B-B$  would emerge as  $o$ . The intensities and directions of vibration of these two rays at this point are represented by the double arrows. When these rays meet the analyzer above they would again each be resolved and their components which vibrate in the plane  $A-A$  would emerge from the analyzer. In this way it is seen that, except at the special points where complete interference takes place, light will result in the interference figure at all points away from the center of the figure and from the lines  $P-P$  and  $A-A$ . From the consideration of Fig. 564 it is evident that the greatest amount of light will come through the section at the  $45^\circ$  points, such as  $B$ . When viewed in monochromatic light, therefore, the interference figure consists of a series of concentric dark and light rings crossed by a vertical and a horizontal dark brush intersecting in the center of the field of the microscope, like Fig. 565.

If a basal section of a uniaxial mineral while in the conoscope is viewed in daylight colored rings will take the place of the light and dark rings observed in the monochromatic light. The change will be like that shown by the quartz wedge in the similar case described in Art. 343. Where the first few dark rings near the center of the figure were formed by the interference of rays having the wave-length of sodium, light colored rings will result in the daylight illumination. These rings will be composed of all the components of white light with the yellow of sodium subtracted. The other colors are obtained in a similar manner by the elimination though interference of some particular wave-length of light. While the interference figure when illuminated in the monochromatic light showed a large number of distinct black rings in daylight, the corresponding colored rings are limited in number and their colors, gradually becoming fainter as the distance from the center of the figure increases, finally merge into the white of the higher order. This is due to the overlapping of the interference rings of the various colors in the same manner as observed in the quartz wedge, see Art. 343. The interference figure viewed in daylight will of course retain the black cross and center since these are due to the cutting out of all the light by the analyzer and are not the result of interference.

The distance of each successive ring from the center of the interference



Uniaxial Interference Figure

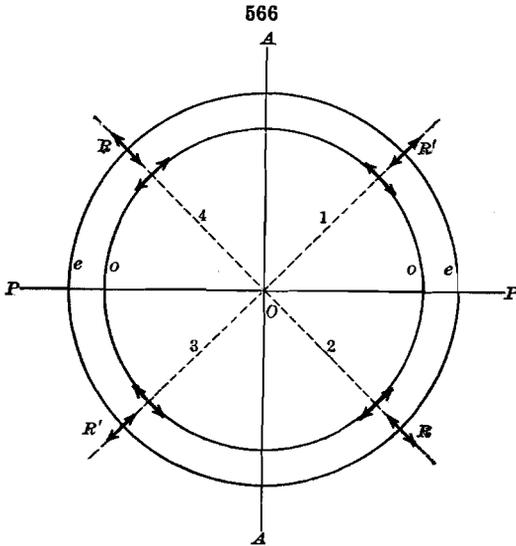
figure obviously depends upon the birefringence, or the difference between the refractive indices, for the ordinary and extraordinary ray, and also upon the thickness of the plate. The stronger the double refraction and the thicker the plate, the smaller the angle of the light-cone which will give a certain amount of retardation, or, in other words, the nearer the circles will be to the center. Further, for the same section the circles will be nearer for blue light than for red, because of their shorter wave-length. When the plate is either quite thin or quite thick only the black brushes will be distinctly seen.

**390. Determination of the Positive or Negative Character of the Birefringence of a Uniaxial Mineral from Its Interference Figure.**

*Use of the Mica Plate.* — For the identification of a uniaxial mineral it is naturally important to determine whether the character of its birefringence is positive or negative. This can usually be best accomplished by tests made upon its interference figure. One of the common ways of making this test is by the use of a sheet of muscovite mica, cleaved so thin that, of the two rays of light passing through it, one has gained one quarter of a wave-length in phase over the other. The mica is usually mounted between long and narrow glass plates and is known as the one quarter wave-length mica plate. It is

commonly marked  $1/4M$  with an arrow indicating the  $Z$  optical direction. In testing an interference figure by means of the mica plate the latter is inserted somewhere between the polarizer and analyzer (in the microscope commonly through the slot just above the objective) and is so orientated that the  $Z$  direction makes an angle of  $45^\circ$  with the planes of vibration of the nicols.

In Fig. 566 let  $P-P$  represent the plane of vibration of the polarizer and  $A-A$  the plane of vibration of the analyzer of a conoscope. Let  $O$  be the point of emergence of the optic axis of a positive uniaxial mineral.



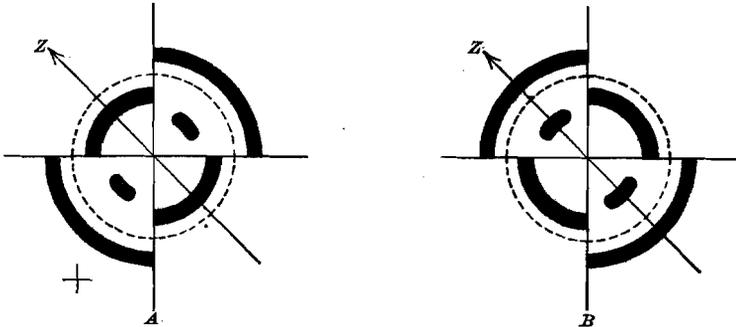
Suppose a single conical ray of light enters the section. It is broken up in the mineral into two rays,  $o$  and  $e$ , which emerge from the section along the arcs of the circles shown in Fig. 566. The trace of the ordinary ray,  $o$ , will be within that of the extraordinary ray,  $e$ , because in a positive mineral the  $o$  ray travels the faster and is less refracted. The directions of vibration of these two rays at the  $45^\circ$  points  $R$  and  $R'$  are represented by the double-headed arrows. When these rays reach the analyzer they will be resolved into components vibrating parallel to  $A-A$ . There are an infinite number of such rays entering and passing through the mineral section with varying angles of inclination and therefore varying lengths of path. At some certain distance out from the center  $O$  two rays will emerge on the same circle with a difference of phase of one

whole wave-length and when resolved in the upper nicol into rays vibrating in the same plane will interfere with each other and produce the first dark ring of the interference figure as it is viewed in monochromatic light.

If the mica plate is introduced above the section a change in the interference figure is noted. The optical character of the mica cannot be fully explained at this point. It is sufficient for present purposes to know that it is a doubly refracting mineral which breaks light up into two rays which are polarized in planes at right angles to each other and which, traveling with different velocities through the mica, will emerge from it with different phases. As stated above, the mica plate is cleaved to the requisite thickness so that the two rays emerge from it with a difference of phase of one quarter of a wave-length. Consider what takes place when such a plate is introduced above the section represented in Fig. 566 in such a position that its vibration direction  $Z$  is parallel to the direction  $R-O-R$  of the figure. Consider what takes place at the points  $R$ . There the vibration direction of the  $e$  ray coincides with the vibration direction  $Z$  of the mica plate. These vibration directions in each case are those of the rays traveling with the smaller velocity. On the other hand, at the same point the vibration direction of the  $o$  ray in the mineral coincides with the vibration direction  $X$  in the plate, both of these being of the rays with the greater velocity. So at this point the effect of the mica plate is to increase the difference of phase between  $o$  and  $e$  and to produce the same result as if the mineral section had been thickened. Consequently the interference rings along the line  $R-O-R$  are increased in number and drawn toward the center of the figure. At the points  $R'$  the opposite is true. The vibration direction of  $e$  coincides now with that of  $X$  in the mica plate; the direction of least velocity in the mineral with that of the greatest in the mica. Also the vibration direction of  $o$  coincides with that of  $Z$ ; that of the greater velocity in the mineral with the less velocity in the mica. So at this point the mica will decrease the difference in phase between  $o$  and  $e$  and produce the effect of thinning the section and so spreading the interference rings farther apart along the line  $R'-O-R'$ . In quadrants 2 and 4, therefore, the rings will be drawn nearer the center, while in quadrants 1 and 3 they will be spread farther apart. Another effect caused by the introduction of the mica plate is even more pronounced. In quadrants 1 and 3, in the case illustrated in Fig. 566, black dots will appear near the center of the figure. In the interference figure, before the introduction of the mica plate, there were points in quadrants 1 and 3 at short distances from the center,  $O$ , where the two rays,  $o$  and  $e$ , emerged from the section with a difference of phase of one quarter wave-length. Under these conditions no interference could take place and these spots were light. The effect of the mica plate in these two quadrants is to everywhere reduce the birefringence due to the mineral by one quarter of a wave-length. Therefore at these two points the difference of phase caused by the birefringence of the mineral is annulled by the mica plate and consequently at these points interference will result and black dots appear. The mica plate produces still other effects. The brushes which were dark in the interference figure become light. Light coming from the crystal section along the lines of the brushes is vibrating only in the vibration direction of the polarizer and ordinarily is wholly cut out by the analyzer above. But with the mica plate intervening this light is broken up in the mica into two rays which vibrate in the vibration planes of the mica and as these are inclined to the plane of the analyzer a portion of the light will come through to the eye. As the light coming from

the section along the lines of the brushes had only a single velocity (was entirely either the ordinary or extraordinary ray) there are only two rays emerging from the mica plate along these directions and their difference of phase is one quarter of a wave-length. Under these conditions there can be no interference and white brushes result. In the same way the dark center of the interference-figure becomes light.

567



Determination of Optical Character with Mica Plate

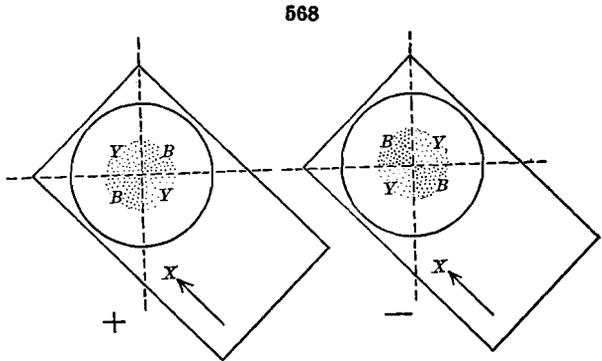
Fig. 567, A, is a diagrammatic representation of the interference figure of a positive mineral as affected by the insertion of the mica plate, the direction of the arrow indicating the direction  $Z$  of the mica, *i.e.*, the direction of vibration of the ray having the smaller velocity. In the case of a negative mineral the conditions as described above will be completely reversed. Fig. 567, B, represents the appearance of an interference figure of a negative mineral when the mica plate is used.

Therefore, to determine the optical character of a uniaxial mineral from its interference figure insert a mica plate above the section with its  $Z$  direction making  $45^\circ$  with the vibration planes of the nicols. Then, if this direction  $Z$  is at right angles to a line joining the two black dots that appear near the center of the figure (*i.e.*, the two lines form a plus sign), the mineral is positive; if, on the other hand, these two directions coincide (form together a minus sign) the mineral is negative.

*Use of the Sensitive Tint.* — The sensitive tint, see Art. 344, is used to determine the positive or negative character of a uniaxial mineral from its interference figure when the mineral section is so thin, or the mineral possesses such a low birefringence, as to show in the figure only a black cross without any rings. Under such conditions the mica plate would not give a decisive test. The sensitive tint is usually so mounted that its longer direction coincides with the direction of the vibration of the faster ray, *i.e.*, the direction  $X$ . The sensitive tint is introduced somewhere between the polarizer and analyzer in such a position that its vibration directions are at  $45^\circ$  with the planes of vibration of the nicols. Let it be assumed that we have the interference figure from a positive mineral, such as is represented in Fig. 566. If the sensitive tint is introduced in such a position that its  $X$  direction is parallel to the line  $R-O-R$  the  $X$  direction of the sensitive tint will be parallel to the direction of vibration of the  $e$  ray in the mineral. Since the mineral is positive the  $e$  ray will have the smaller velocity and therefore in quadrants 2 and 4 the

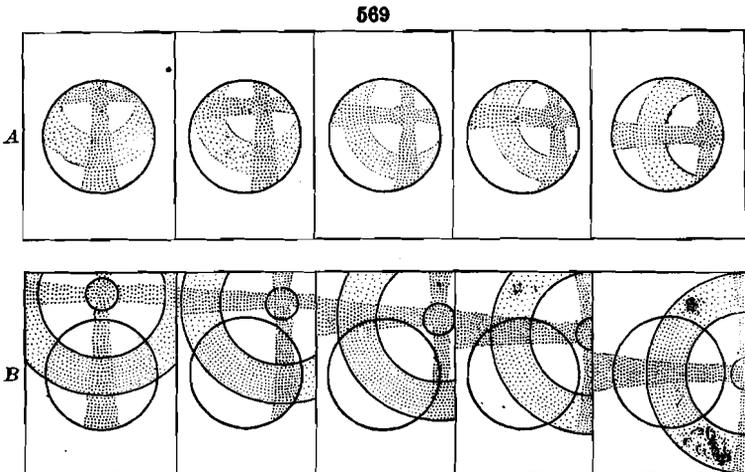
optical orientation of the mineral and the sensitive tint will be opposed to each other. The sensitive tint alone would produce an interference color of red of the first order. But if the effect of the birefringence of the mineral is such as to subtract from the birefringence of the sensitive tint the color will change to yellow. Consequently in these quadrants yellow spots will appear near the center of the field at the points where the effect of the mineral has been sufficient to lower the interference color to that extent. In the other quadrants, 1 and 3, the faster and slower rays of the mineral and sensitive tint coincide in their directions and the effect of the two substances is an additive one. Consequently in these two quadrants the color will rise to blue.

In making the above test with the sensitive tint it is convenient to follow the rule that if the direction *X* of the sensitive tint crosses a line uniting the two blue dots (makes a plus sign) the mineral is positive; if, on the other hand, these two directions coincide (make together a minus sign) the mineral is negative. These conditions are illustrated in Fig. 568.



Determination of Optical Character with Sensitive Tint

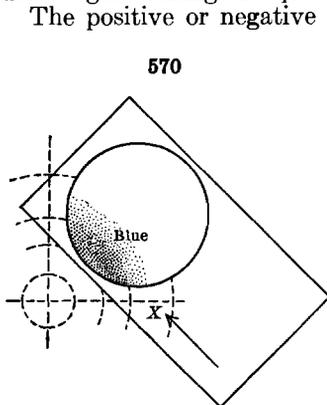
391. Interference Figures from Inclined Sections of Uniaxial Minerals.



Eccentric Uniaxial Interference Figures

— It frequently happens that a mineral section under observation for an interference figure is not cut exactly parallel to the basal plane of the crystal.

An interference figure obtained from such an inclined section will of course be eccentric to the microscope field. If the section is inclined only a little to the basal plane, the center of the figure (*i.e.*, the point of emergence of the optic axis) will still be within the field of vision and will move in a circle about the center of the field when the section is revolved upon the microscope stage. Fig. 569, A, shows the successive positions of such an interference figure during revolution. If the section is more sharply inclined the center of the interference figure may be quite outside the field. As the section is turned on the stage the four arms of the interference cross will traverse the field in succession. They will move across the field as straight bars and, provided the section has been cut not too highly inclined to the optic axis, will move across the field parallel to the cross-hairs of the microscope. This fact is of importance in order to distinguish such a uniaxial interference figure from certain biaxial figures. The latter will often show similar bars which, however, will always curve as they cross the field of the microscope. If the first of these bars in the uniaxial figure moves from left to right across the field, the second will move from the top to the bottom, the third from right to left and the last from the bottom to the top, etc. Fig. 569, B, shows the different position of such a figure during one quarter of a revolution.



Sensitive Tint with  
Eccentric Interference Figure

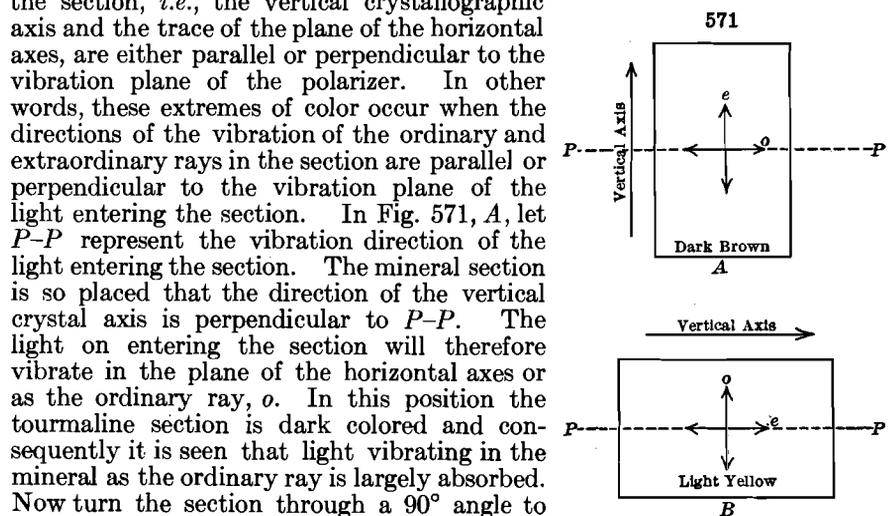
The positive or negative character of the mineral can usually be determined from an eccentric figure if care is taken to make certain which quadrant is visible when the test is made. For instance, in Fig. 570 is shown how the test is made with the sensitive tint upon the eccentric interference figure of a positive mineral.

In examining unorientated sections of a mineral, such as the random section found in a rock section or the small fragments of a mineral placed upon a glass slide, it is advisable always to hunt for that section that gives the lowest interference color. The amount of birefringence shown in various sections of a uniaxial mineral decreases as the section approaches the orientation of the basal plane. Consequently that section showing the lowest interference color will yield the most nearly symmetrical interference figure.

**392. Interference Figure from a Prismatic Section of a Uniaxial Mineral.** — When a prismatic section of a uniaxial mineral is examined for an interference figure an indefinite result is obtained. The figure is analogous to one obtained in the case of biaxial crystals. The reasons for this resemblance will be pointed out in a later article. The two types of figures cannot be in this case easily differentiated. Two dark and usually indefinite hyperbolas approach each other as the section is turned on the microscope stage, form an indistinct cross, and rapidly separate. These bars differ from those obtained in a biaxial interference figure in that they rapidly fade out as they move away from the crossed position. This type of interference figure can be obtained easily from the quartz wedge.

**393. Absorption Phenomena of Uniaxial Crystals. Dichroism.** — When light enters colored minerals as rays of white light, *i.e.*, containing vibra-

tions of all wave-lengths from that of violet light at one end of the spectrum to that of red light at the other, certain wave-lengths will be absorbed during the passage of the light through the mineral, so that the light, as it emerges, has a definite color. It happens in certain deeply colored minerals that the amount and character of this absorption depends upon the direction of the light vibration. For instance in the case of uniaxial minerals, the ordinary and extraordinary rays may emerge from the section with distinctly different colors. Take, for instance, a prismatic section of a brown colored tourmaline and observe it in plane polarized light without the use of the upper nicol. As the section is revolved upon the stage of the polariscope the color may change from a dark brown to a light yellow-brown. The greatest difference in the color occurs at positions 90° apart and when the crystallographic directions of the section, *i.e.*, the vertical crystallographic axis and the trace of the plane of the horizontal axes, are either parallel or perpendicular to the vibration plane of the polarizer. In other words, these extremes of color occur when the directions of the vibration of the ordinary and extraordinary rays in the section are parallel or perpendicular to the vibration plane of the light entering the section. In Fig. 571, *A*, let *P-P* represent the vibration direction of the light entering the section. The mineral section is so placed that the direction of the vertical crystal axis is perpendicular to *P-P*. The light on entering the section will therefore vibrate in the plane of the horizontal axes or as the ordinary ray, *o*. In this position the tourmaline section is dark colored and consequently it is seen that light vibrating in the mineral as the ordinary ray is largely absorbed. Now turn the section through a 90° angle to the position shown in Fig. 571, *B*. In this position the light must vibrate in the section wholly as the extraordinary ray, *e*, and the color is a light yellow-brown. Therefore the extraordinary ray is only slightly absorbed. This difference in the absorption or the color of the two rays is known as *dichroism*. Either the ordinary or the extraordinary ray may be the most absorbed and the two cases are expressed as either  $o > e$  ( $\omega > \epsilon$ ) or  $e > o$  ( $\epsilon > \omega$ ). In uniaxial minerals dichroism is to be best observed in prismatic sections where it attains its full intensity. Basal sections show no dichroism, since light passing through the section parallel to the optic axis must all vibrate in the horizontal axial plane and belong wholly to the ordinary ray.



An instrument called a *dichroscope*, contrived by Haidinger, is sometimes used for examining this property of crystals. An oblong rhombohedron of Iceland spar is placed in a metallic cylindrical case, having a convex lens at one end, and a square hole at the other. On looking through it, the square hole appears double; one image belongs to the ordinary and the other to the extraordinary ray. When a pleochroic crystal is examined with it by transmitted light, on revolving it the two squares, at intervals of 90° in the revolution, have different colors, corresponding to the vibration-planes of the ordinary and extraordinary ray in calcite. Since the two images are situated side by side, a very slight difference of color is perceptible. A similar device is sometimes used as an ocular in the microscope.

**394. Circular Polarization.** — The subject of elliptically polarized light and circular polarization has already been briefly alluded to in Art. 350. This phenomenon is most distinctly observed among minerals in the case of crystals belonging to the rhombohedral-trapezohedral class, that is, quartz and cinnabar.

It has been explained that a section of an ordinary uniaxial crystal cut normal to the vertical (optic) axis appears dark in parallel polarized light for every position between crossed nicols. If, however, a similar section of quartz, say 1 mm. in thickness, be examined under these conditions, it appears dark in monochromatic light only, and that not until the analyzer has been rotated so that its vibration-plane makes for sodium light an angle of  $24^\circ$  with that of the polarizer. In other words, this quartz section has rotated the plane of vibration some  $24^\circ$ , and here either to the right or to the left, looking in the direction of the light. The amount of this rotation increases with the thickness of the section, and, as the wave-length of the light diminishes (for red this angle of rotation for a section of 1 mm. is about  $19^\circ$ , for blue  $32^\circ$ ). The direction of the rotation is to the right or left, as defined above — according as the crystal is crystallographically right-handed or left-handed (p. 113).

If the same section of quartz (cut perpendicular to the axis) be viewed between crossed nicols in converging polarized light, it is found that the interference-figure differs from that of an ordinary uniaxial crystal. The central portion of the black cross has disappeared, and instead the space within the inner ring is brilliantly colored.\* Furthermore, when the analyzing nicol is revolved, this color changes from blue to yellow to red, and it is found that in some cases this change is produced by revolving the nicol to the *right*, and in other cases to the *left*; the first is true with right-handed crystals, and the second with left-handed. If sections of a right-handed and left-handed crystal are placed together in the polariscope, the center of the interference-figure is occupied with a four-rayed spiral curve, called, from the discoverer, *Airy's spiral*. Twins of quartz crystals are not uncommon, consisting of the combination of right- and left-handed individuals (according to the Brazil law) which show these spirals of Airy. With cinnabar similar phenomena are observed. Twins of this species also not infrequently show Airy's spirals in the polariscope.

**395. Summary of the Optical Characters of Uniaxial Crystals.** — All sections of uniaxial crystals show double refraction except those that are cut parallel to the basal plane. All doubly refracting sections show parallel extinction. When viewed in convergent polarized light with crossed nicols all sections show a characteristic uniaxial interference figure except those that lie in the prism zone of the crystal or that are only slightly inclined to that zone. All doubly refracting sections have two refractive indices corresponding to the two extinction directions: one of these is *always*  $\omega$  and the other has a value ( $\epsilon'$ ) ranging from  $\omega$  to  $\epsilon$ , dependent on the inclination of the section to the optic axis. Dark colored minerals may show dichroism. Tetragonal and hexagonal substances cannot be distinguished from each other by optical tests. They may be at times told apart by characteristic cross sections of their crystals.

## C. BIAXIAL CRYSTALS

### *General Optical Relations*

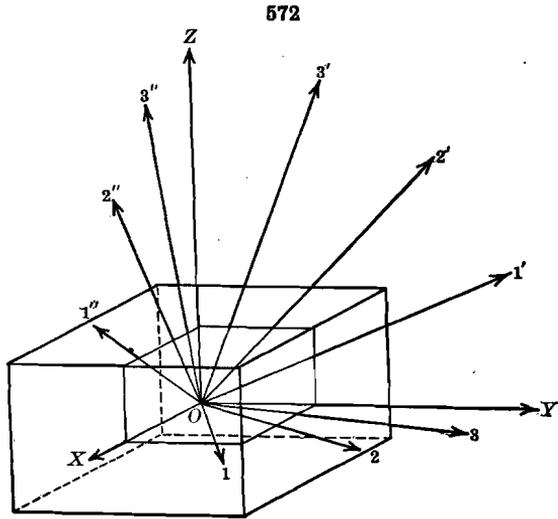
The crystals of the remaining systems, *i.e.*, the orthorhombic, monoclinic, and triclinic belong optically to what is known as the Biaxial Group.

**396. The Behavior of Light in Biaxial Crystals.** — In biaxial crystals there are three especially important directions at right angles to each other which are designated as *X*, *Y*, and *Z* (also *a*, *b*, and *c*). These three directions are sometimes spoken of as *axes of elasticity* in reference to certain assumed differences in the ether along them. The nature of these three directions is as follows. Light which results from vibrations parallel to *X* (axis of greatest elasticity) is propagated with the maximum velocity; that from vibra-

\* Very thin sections of quartz, however, show (*e.g.*, with the microscope) the dark cross of an ordinary uniaxial crystal.

tions parallel to  $Z$  (axis of least elasticity) with minimum velocity; and that from vibrations parallel to  $Y$  with an intermediate velocity. It is to be emphasized that these directions,  $X$ ,  $Y$ , and  $Z$  refer to directions of vibration and not to directions of propagation. Corresponding to the maximum, intermediate, and minimum light velocities are three principle indices of refraction, designated respectively as  $\alpha$ ,  $\beta$ , and  $\gamma$ . Of these  $\alpha$ , belonging to light with the maximum velocity, will have the least value and  $\gamma$  belonging to light with the minimum velocity, will have the greatest value. The value of  $\beta$  will be intermediate between the other two, sometimes being nearer to  $\alpha$  and at other times being nearer to  $\gamma$ ; it is not the arithmetical mean between them. The various methods of determining the values of these three principal indices of refraction will be considered in a later article.

In studying the propagation of light within a biaxial crystal let it be assumed that Fig. 572 represents a rectangular parallelepiped in which the front to back axis is the direction  $X$ , the left to right axis is  $Y$ , and the vertical axis is  $Z$ . In



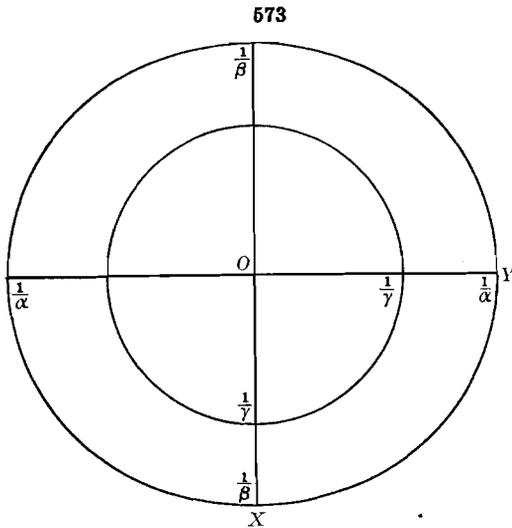
572

connection with the figure and those which follow it is helpful to make use of a model (a pasteboard box would answer) orientated so that its longer edge runs from front to back, its mean edge from left to right and its shortest edge vertical, corresponding to the  $X$ ,  $Y$ , and  $Z$  directions of the figure. In the development of the figures that follow it has been assumed that the three principle indices of refraction are  $\alpha = 1.5$ ,  $\beta = 1.6$ ,  $\gamma = 2.5$ , a difference between  $\alpha$  and  $\gamma$  far exceeding anything observed in actual crystals. In general, this difference does not exceed 0.1; hence it is necessary to greatly exaggerate the actual values in order that the phenomena may be distinctly shown by diagrams drawn on a small scale.

In the discussion that follows it will be assumed that light originates at the center of a crystal,  $O$ , Fig. 572, and the endeavor will be made to determine the character of the rays which radiate from  $O$  in all directions. The simplest directions, and the ones which in reality are the most important, are those that lie in the axial planes of the figure,  $XOY$ ,  $YOZ$ , and  $XOZ$ . These will be considered first.

Consider the plane of the  $X$  and  $Y$  directions, Fig. 572. Light will radiate from  $O$  toward  $X$  and  $Y$  and in all intermediate directions with vibrations parallel to  $Z$  and hence traveling with a uniform and at the same time minimum velocity,  $1/\gamma$ . The distance such light will travel in a given moment of time may be plotted by drawing a circle about  $O$  with the radius,  $1/\gamma$ , Fig. 573. In the direction  $OX$  there must also travel a second polarized ray result-

ing from vibrations parallel to  $OY$ , hence traveling with mean velocity  $1/\beta$ . Likewise in the direction  $OY$  there will be a ray resulting from vibrations

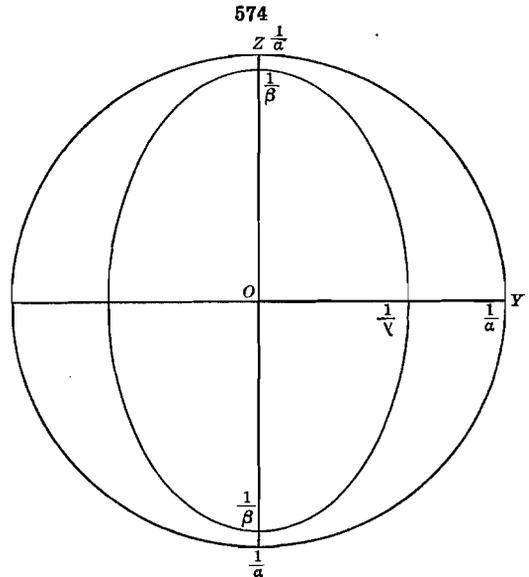


parallel to  $OX$ , hence traveling with the maximum velocity,  $1/\alpha$ . In all directions intermediate between  $X$  and  $Y$  the light velocities will be proportional to the radii of an ellipse having  $1/\beta$  and  $1/\alpha$  respectively as its semi-minor and semi-major diameters, Fig. 573. In the plane of the  $X$  and  $Y$  directions, therefore, in a given moment of time light will radiate from the center as ordinary and extraordinary rays, the wave fronts being represented by a circle within an ellipse.

Consider next the plane of the  $Y$  and  $Z$  directions, Fig. 572. Light will radiate

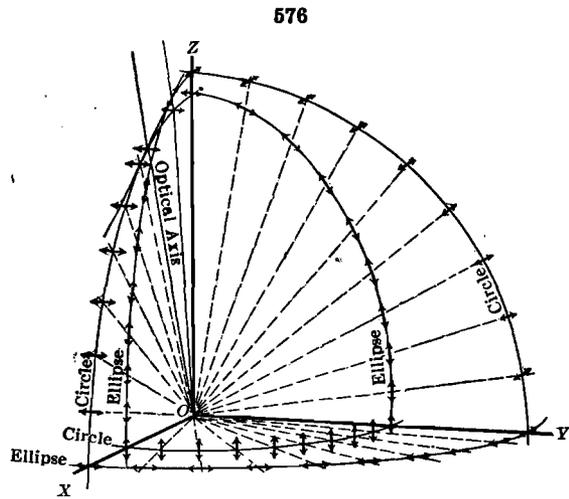
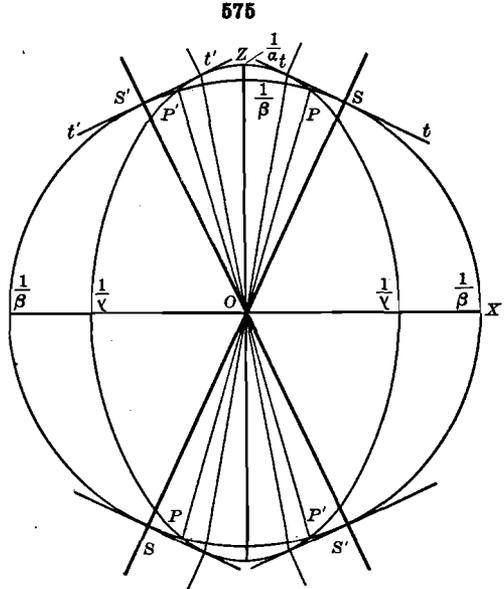
from  $O$  toward  $Y$  and  $Z$  and in all intermediate directions resulting from vibrations parallel to  $OX$ . It will therefore travel with uniform and the

maximum velocity,  $1/\alpha$ . The distance traveled in a given moment of time may be plotted by drawing a circle about  $O$  with the radius  $1/\alpha$ , Fig. 574. Likewise there will travel in the direction  $OY$  a second ray resulting from vibrations parallel to  $OZ$ , hence moving with the minimum velocity,  $1/\gamma$ . Also in the direction  $OZ$  there will be a ray resulting from vibrations parallel to  $OY$  with the velocity  $1/\beta$ . In directions intermediate between  $Y$  and  $Z$  the light velocities will be proportional to the radii of an ellipse having  $1/\gamma$  and  $1/\beta$  respectively as its semi-minor and semi-major diameters, Fig. 574. In



the plane of the  $Y$  and  $Z$  directions, therefore, in a given moment of time, light will radiate from the center as ordinary and extraordinary rays, the wave fronts being represented by an ellipse within a circle.

The last and most important plane to be considered is that of the  $X$  and  $Z$  directions, Fig. 572. Light will radiate from  $O$  toward  $X$  and  $Z$  and all intermediate directions with vibrations parallel to  $OY$ , hence traveling with a uniform and intermediate velocity,  $1/\beta$ . The distance traveled in a given moment of time is represented in Fig. 575 by the circle with the radius  $1/\beta$ . There will likewise travel in the direction  $OZ$  a ray resulting from vibrations parallel to  $OX$ , hence moving with the maximum velocity,  $1/\alpha$ . Also a ray will travel in the direction  $OX$  with vibrations parallel to  $OZ$ , hence having the minimum velocity,  $1/\gamma$ . In intermediate positions the light velocity will be proportional to the radii of an ellipse with  $1/\alpha$  and  $1/\gamma$  respectively as its semi-major and semi-minor diameters, Fig. 575. In the plane of the  $X$  and  $Z$  directions, therefore, in a given moment of time, light will radiate from the center as ordinary and extraordinary rays, the wave fronts represented by a circle intersecting an ellipse. It is to be noted that in this last plane there are four points where the two wave fronts coincide. In other words, light traveling along the radial lines connecting these points will be moving with uniform velocity and consequently along these directions there will be no double refraction. These directions are known as the optic axes of the crystal and since there are two of them the optical group is spoken of as biaxial. The character of these optic axes will be more fully developed in a later article.

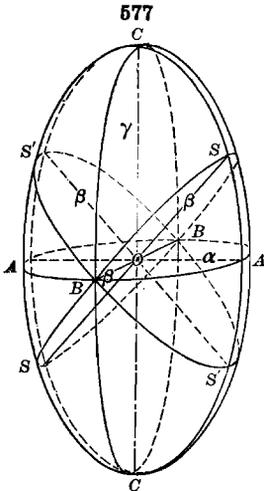


crystal have been discussed. Fig. 576 represents the wave fronts in these three planes as they appear when bounding one octant. The complete wave

surfaces for light propagated in all directions consist of warped figures which conform to the circular or elliptical wave fronts already described in the three principal planes and have intermediate positions elsewhere. The only satisfactory way to represent these complete surfaces is by means of a model.

**397. Biaxial Indicatrix.** — It is found further that the optical structure of a biaxial crystal can be represented by an ellipsoid, known as the *indicatrix*, having as its axes three lines which are at right angles to each other and proportional in length to the indices  $\alpha, \beta, \gamma$ . This is analogous to the similar figure for uniaxial crystals described in Art. 382.

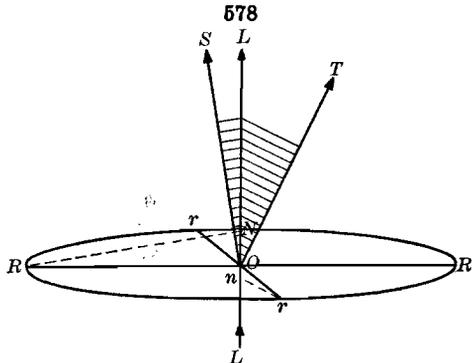
This ellipsoid, whose axes represent in magnitude the three principal refractive indices,  $\alpha, \beta, \gamma$  (where  $\alpha < \beta < \gamma$ ), (see Fig. 577), not only exhibits the character of the optical symmetry, but from it may be derived the direction, velocity and plane of vibration of any light ray traversing the crystal.



Biaxial Indicatrix

In general it may be stated that the character of the two light rays which result from a single incident ray may be derived from a study of that elliptical section of the indicatrix which is normal to the incident ray. If this section happens to be one of the three principal sections of the indicatrix, *ABAB*, *ACAC*, or *BCBC*, Fig. 577, its major and minor diameters give the directions of vibration and their semi-lengths the indices of refraction of the two rays. If the incident ray has some direction different from the directions of the

three axes of the indicatrix ellipsoid the derivation of the character of the two refracted rays is not as simple. Let Fig. 578 represent such an elliptical section normal to the inclined ray *L-L*. In this case the major and minor diameters *R-O-R* and *r-O-r* of the elliptical section lie in the vibration planes of the two rays but the directions of vibration of the latter will be somewhat inclined to the elliptical section. These directions of vibration may be obtained by erecting normals to the surface of the indicatrix at the points *R* and *r* where the major and minor diameters of the elliptical section meet that surface. These normals *RN* and *rn*, when extended to the line of the incident ray *L-L*, yield the directions of vibration and the refractive indices of the two refracted rays. Their directions of transmission (the lines *OS* and *OT*) will be perpendicular to these normals and since neither of the latter lie in the elliptical section both rays will be refracted and behave as extraordinary rays.

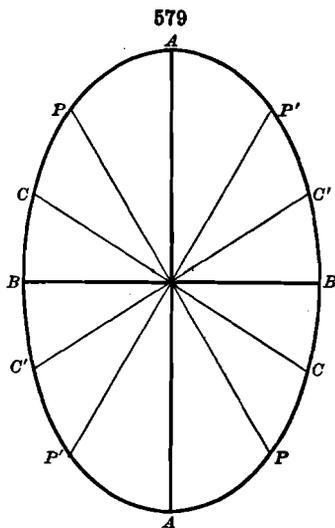


There are two special sections of the indicatrix that require notice. The

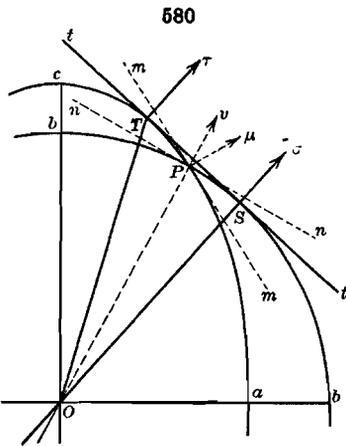
line  $B-O-B$  (Fig. 577) is longer than the line  $A-O-A$  but shorter than the line  $C-O-C$ . Obviously, in some position intermediate between  $A-O-A$  and  $C-O-C$  there will be a diameter of the ellipse  $ACAC$  which will be equal in length to  $B-O-B$ . There are two such lines, as  $S-O-S$  and  $S'-O-S'$  in Fig. 577. The major and minor diameters of these sections of the indicatrix,  $BSBS$  and  $BS'BS'$ , are equal and the sections therefore become circles. Consequently light passing through a section of a crystal cut parallel to either of these circular sections of its indicatrix will have a uniform velocity and may vibrate in any transverse direction. In other words, there will be no double refraction along the lines normal to these two sections. These lines constitute what are known as the primary optic axes of the crystal; see further in Art. 398.

The major and minor diameters of any section of the indicatrix yield the traces upon that section of the planes of vibrations of the two rays into which the ray normal to the section is refracted. In other words, the major and minor diameters of the elliptical section of the indicatrix give the directions of extinction of a crystal section having this optical orientation. Further, these extinction directions bisect the angles made by the traces upon the section of two planes, each of which includes the pole of the section and one of the two optic axes. This may be demonstrated by aid of Fig. 579 which represents a general elliptical section of an indicatrix.  $A-A$  and  $B-B$  are the major and minor diameters of the ellipse and so represent the extinction directions of the mineral section.  $C-C$  and  $C'-C'$  represent the intersections of the two circular sections of the indicatrix with this elliptical section. As these lines are diameters of equal circles they must be equal in length and it therefore follows from the geometrical nature of an ellipse that the angles  $AOC$  and  $AOC'$  are equal. Let the line  $P-P$  represent the intersection with this elliptical section of a plane in which lie the normal to the section and one of the optic axes.

Since this plane includes an optic axis it must be perpendicular to the circular section of the indicatrix of which the line  $C'-C'$  is a diameter. Also since this plane includes the normal to the elliptical section under consideration it must be at right angles to the latter plane. Under these conditions it is obvious that the lines  $P-P$  and  $C'-C'$  in Fig. 579 must be at right angles to each other. In the same way it can be proved that the lines  $P'-P'$  and  $C-C$  are also at right angles to each other. Since the angles  $AOC$  and  $AOC'$  are equal and the angles  $POC'$  and  $P'OC$  are also equal it follows that the angles  $AOP$  and  $AOP'$  are likewise equal. In other words the lines  $A-A$  and  $B-B$  representing the directions of extinction of the section bisect the angles made by the traces upon the section of the two planes which respectively pass through each optic axis and the normal to the section. This fact will be made use of later, see Art. 407, in explaining the characters of the biaxial interference figure.



**398. Primary and Secondary Optic Axes.** — It has already been stated (Art. 397) that there are two directions, namely, those normal to the circular



cross sections of the indicatrix ( $SS, S'S'$ , Fig. 577) in which all light is propagated with uniform velocity. Hence in these directions there can be no double refraction within a crystal; nor is there when the ray emerges. These two directions bear so close an analogy to the optic axes of a uniaxial crystal that they are also called *optic axes*, and the crystals here considered are hence named *biaxial*. In Fig. 575, which represents a cross section of the wave-surfaces in the plane of the  $X$  and  $Z$  directions, these optic axes have the direction  $SS, S'S'$  normal to the tangent planes  $tt, t't'$ , and the direction of the external wave is given by the normal  $S\sigma$  (Fig. 580).

Properly speaking the directions mentioned are those of the *primary optic axes*, for there are also two other somewhat analogous directions,  $PP, P'P'$ , of Fig. 575, called for sake of distinction the *secondary optic axes*. The properties of the latter directions are obvious from the following considerations.

In the section of the wave-surface shown in Fig. 575 (also enlarged, in Fig. 580), corresponding to the axial plane  $XZ$ , it is seen that the circle with radius  $\frac{1}{\beta}$  intersects the ellipse whose major and minor axes are  $\frac{1}{\alpha}$  and  $\frac{1}{\gamma}$  in the four points  $P, P, P', P'$ . Corresponding to these directions the velocity of propagation is obviously the same for both rays. Hence within the crystal these rays travel together without double refraction. Since, however, there is no common wave-front for these two rays (for the tangent for one ray is represented by  $mm$  and for the other by  $nn$ , Fig. 580) they do suffer double refraction on emerging; in fact, two external light-waves are formed whose directions are given by the normals  $P\mu$  and  $P\nu$ . These directions,  $PP, P'P'$ , therefore, have a relatively minor interest, and whenever, in the pages following, optic axes are spoken of, they are always the *primary optic axes*, that is, those having the directions  $SS, S'S'$  (Fig. 575), or  $OS$ , Fig. 580. In practice, however, as remarked in the next article, the angular variation between the two sets of axes is usually very small, perhaps  $1^\circ$  or less.

**399. Interior and Exterior Conical Refraction.** — The tangent plane to the wave-surface drawn normal to the line  $OS$  through the point  $S$  (Fig. 580) may be shown to meet it in a small circle on whose circumference lie the points  $S$  and  $T$ . This circle is the base of the interior cone of rays  $SOT$ , whose remarkable properties will be briefly hinted at. If a section of a biaxial crystal be cut with its faces normal to  $OS$ , those parallel rays belonging to a cylinder having this circle as its base, incident upon it from without, will be propagated within as the cone  $SOT$ . Conversely, rays from within corresponding in position to the surface of this cone will emerge *parallel* and form a circular cylinder. This phenomenon is called *interior conical refraction*.

On the other hand, if a section be cut with its faces normal to  $OP$ , those rays having the direction of the surface of a cone formed by perpendiculars to  $mm$  and  $nn$  will be propagated within *parallel* to  $OP$ , and emerging on the other surface form without a similar cone on the other side. This phenomenon is called *exterior conical refraction*.

In the various figures given (573–580) the relations are much exaggerated for the sake

of clearness; in practice the relatively small difference between the indices of refraction  $\alpha$  and  $\gamma$  makes this cone of small angular size, rarely over  $2^\circ$ .

**400. Optic Axial Angle. Bisectrices. Positive and Negative Biaxial Crystals.** — The optic axes always lie in the plane of the  $X$  and  $Z$  optical directions; this plane is called the optic axial plane (or, briefly, ax. pl.). It is obvious from a consideration of the indicatrix ellipsoid that the position of its circular sections and consequently of the optic axes normal to them, will vary with a variation in the relative values of the indices of refraction. As already stated the index  $\beta$  is not an arithmetical mean between  $\alpha$  and  $\gamma$  but may at times be nearer to  $\alpha$  than to  $\gamma$  or the reverse. As these relations change, the shape of the indicatrix and the position of its circular sections and the angle between the optic axes will also change. The mathematical relations between the optic axial angle and the principle refractive indices are given in the next article. From the above it is obvious that for certain relative values of the refractive indices, the optic angle must be  $90^\circ$ .\* Such a case, however, is rarely observed and when it occurs it is true for light of a certain color † (wave-length) only and not for others.

The  $X$  and  $Z$  optical directions bisect the angles between the optic axes and are therefore known as *bisectrices*. The one that bisects the acute axial angle is called the *acute bisectrix* (or  $Bx_a$ ) while the one bisecting the obtuse angle is the *obtuse bisectrix* (or  $Bx_o$ ). If the word *bisectrix* is used alone without special qualification it is always to be understood as referring to the acute bisectrix.

Either  $X$  or  $Z$  may be the acute bisectrix. If  $X$  is the acute bisectrix the substance is said to be *optically negative*, while if  $Z$  is the acute bisectrix it is *optically positive*.

Roughly expressed, the optic axes will lie nearer to  $Z$  than to  $X$  — that is,  $Z$  will be the bisectrix — when the value of the intermediate index,  $\beta$ , is nearer to that of  $\alpha$  than to that of  $\gamma$ . It is obvious (cf. Fig. 575) that in this case, as the angle diminishes and becomes nearly equal to zero, the form of the ellipsoid then approaches that of the prolate spheroid of the positive uniaxial crystal as its limit (Fig. 557, p. 256); this shows the appropriateness of the + sign here used.

On the other hand, the optic axes will lie nearer to  $X$  than to  $Z$  — that is,  $X$  will be the bisectrix — if the value of the mean index  $\beta$  is nearer to that of  $\gamma$  than to that of  $\alpha$ . Such a crystal, for which  $Bx_a = X$ , is called *optically negative*. In this case the smaller the angle the more the ellipsoid approaches the oblate spheroid of the negative uniaxial crystal (Fig. 556, p. 256).

The following are a few examples of positive and negative biaxial crystals:

Positive (+).	Negative (-).
Sulphur.	Aragonite.
Enstatite.	Hypersthene.
Topaz.	Muscovite.
Barite.	Orthoclase.
Chrysolite.	Epidote.
Albite.	Axinite.

\* The axial angle will equal  $90^\circ$  when the indices satisfy the following equation:

$$\frac{1}{\alpha^2} - \frac{1}{\beta^2} = \frac{1}{\beta^2} - \frac{1}{\gamma^2}.$$

† For danburite axial angle =  $89^\circ 14'$  for green (thallium) and  $90^\circ 14'$  for blue ( $\text{CuSO}_4$ ).

**401. Relation of the Axial Angle to the Refractive Indices.** — If in a given case the values of  $\alpha$ ,  $\beta$ , and  $\gamma$  are known, the value of the interior optic axial angle known as  $2V$ ; see also Art. 408, can be calculated from them by the following formulas:

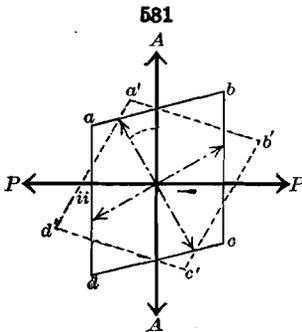
$$\cos^2 V = \frac{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}{\frac{1}{\alpha^2} - \frac{1}{\gamma^2}} \quad \text{or} \quad \tan^2 V = \frac{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}$$

### Examination of Biaxial Crystals in Polarized Light

#### 402. Sections in Parallel Polarized Light with Crossed Nicols.

**Interference Colors.** Thin sections of biaxial crystals when examined between crossed nicols in general show some interference color. This color will depend upon the following factors: *the thickness of the section*, — the thicker the section the higher the order of color; *the birefringence of the substance*, — the higher the birefringence (*i.e.*, the greater the difference between the values of  $\alpha$  and  $\gamma$ ) the higher the order of color; *the optical orientation of the section*, — in general, the nearer the section comes to being parallel to the optic axial plane, in which lie the vibration directions of the fastest and slowest rays, the higher will be its birefringence and the order of its interference color.

**Extinction Directions.** A section which, in general, is colored will show during a complete revolution on the microscope stage four positions at  $90^\circ$  intervals in which it appears dark. These are the positions of extinction, or are those positions in which the vibration planes of the section coincide with those of the nicols. When the directions of extinction of a section are parallel or at right angles to a crystallographic axis or to the trace, upon the section, of a crystallographic axial plane it is said to show *parallel extinction*. If the extinction directions are not parallel to these crystallographic directions the extinction is said to be *inclined*.



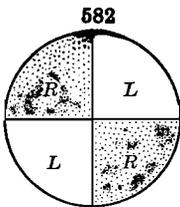
For example, in Fig. 581, let the two larger rectangular arrows represent the vibration directions for the two nicols, and between which suppose a section of a biaxial crystal,  $abcd$ , to be placed so that one edge of a known crystallographic plane coincides with the direction of one of these lines. The vibration directions of the section are indicated by the dotted arrows and as in this position of the section these directions do not coincide with the vibration directions of the nicols the section will appear light. The section will have to be turned to the position  $a'b'c'd'$  in order to achieve this coincidence and so bring about extinction. The angle (indicated in the figure) which it has been necessary to revolve the plate to obtain the effect described, is the angle which one of the vibration directions in the given plate makes with the given crystallographic edge  $ad$ ; it is called the *extinction angle*.

**403. Measurement of the Extinction Angle.** — It frequently becomes important to measure as accurately as possible the extinction angle of a sec-

tion. This is most commonly done with a microscope which is provided with a revolving stage having a graduated circle for measuring angles of rotation. In order to measure an extinction angle it is of course necessary to be able to locate in the section some definite crystallographic direction. This is usually provided by some crystal outline or cleavage crack. This crystallographic direction is brought parallel to one of the cross-hairs of the microscope and the angular position of the microscope stage noted. Then the stage is rotated until the section shows its maximum darkness. The angle between these two positions is the angle of extinction desired. The difficulty in the measurement lies in the accurate determination of the position of maximum extinction. Frequently it is possible to rotate the microscope stage through an arc of one to two degrees without any appreciable brightening of the field. It will help in determining the point of maximum extinction if the plate is turned beyond the point of extinction until the first faint illumination is observed and then back in the other direction until the same strength of illumination occurs. The point half way between these two positions should be very close to the point desired. The measurements should be repeated a number of times and the average taken. It is also advisable to make the measurements on both sides of the position of the crystallographic direction. The illumination in most cases had better be in the monochromatic sodium-light.

Various devices are used at times in order to increase the accuracy with which the position of maximum extinction can be determined.\* The sensitive tint is sometimes used for this purpose. If this is inserted in the diagonal slot of the microscope tube below the analyzer the field will be uniformly colored red of the first order when the section on the microscope stage is at the position of extinction. But if the section is turned, even very slightly, from this position it will also affect the light and change the interference color observed. The sensitive tint in specially favorable cases can be used in this way to advantage but it has been shown that in the majority of cases its use does not materially increase the accuracy of the measurements.

The power of quartz plates cut normal to the vertical crystallographic axis to rotate the plane of polarization of light (see Art. 394) is used in other devices to increase the accuracy of the measurement of the angle of extinction. The *Bertrand ocular* contains four such sectors of quartz; two of these placed diagonally opposite to each other are from a right-handed quartz crystal while the other two are from a left-handed crystal. This ocular is inserted in the microscope tube in place of the regular ocular; the analyzer is pushed out of the microscope tube and a nicol prism mounted in an appropriate holder is placed over the ocular. If this upper nicol is turned about in various positions it will be noted that, in general, opposite quadrants of the field are colored alike but differ in color from the adjacent quadrants, see Fig. 582. But when the plane of the cap nicol is exactly at right angles to the plane of the polarizer below all four quadrants show the same color. If a double refracting mineral be placed on the stage of the microscope with its vibration directions parallel to those of the nicols, since in this position it has no birefringent effect upon the light, the field will still remain uniformly colored. But if the section is turned from its



Bertrand Ocular

\* Detailed descriptions of these various devices with comment on their accuracy are given by F. E. Wright in *The Methods of Petrographic-Microscopic Research*.

position of extinction its birefringent effect is added to that of the two opposite quadrants of the ocular and subtracted from that of the remaining two. Consequently adjacent quadrants become differently colored. A very slight rotation of the section is sufficient to produce an appreciable effect.

Another microscope accessory using the same principle as the Bertrand ocular is the so-called *bi-quartz wedge plate* described by Wright. This consists of two adjacent plates of quartz cut normal to the *c* crystal axis, one from a left-handed and the other from a right-handed crystal. Above these are placed two wedges of quartz, a right-handed wedge above the left-handed plate, etc. At the point where the wedge is equal in thickness to the plate beneath there will be zero rotation of the light and between crossed nicols this will produce a dark line across the field. As the distance increases from this point the amount of rotation of the light increases equally but in opposite directions on either side of the central dividing line of the plate. Both halves of the plate will be equally illuminated if the mineral section is in the position of extinction, but if the latter is turned so that it adds or subtracts its birefringent effect to that of the quartz plate the two halves become differently illuminated. By moving the plate in or out a position can be found where this change in illumination is most marked. This quartz plate is used with a special ocular provided with a slot in such a position that the quartz plate may be introduced into the microscope tube at the focal plane of the ocular and with the medial line of the plate parallel to the plane of vibration of the polarizer. A cap nicol is used above the ocular.

**404. Determination of the Birefringence with the Microscope.** — The value of the maximum birefringence ( $\gamma - \alpha$ ) is obviously given at once when the refractive indices are known. It can be approximately estimated for a section of proper orientation and of measured thickness by noting the interference-color as described in Art. 347.

**405. Determination of the Relative Refractive Power.** — The relative refractive power of the two vibration-directions in a thin section is readily determined with the microscope (in parallel polarized light) by the method of compensation. This is applicable to any section, whatever its orientation and whether uniaxial or biaxial. The methods employed have already been described in Art. 348.

A crystal-section is said to have *positive elongation* if its direction of extension approximately coincides with the ether-axis *Z*; if with *X* the elongation is *negative*. The same terms are also used, in general, according to the relative refractive power of the two directions.

**406. Determination of the Indices of Refraction of a Biaxial Mineral.** — The indices of refraction of a biaxial mineral are determined by the same methods as outlined previously, see Art. 327, the only modification introduced being necessitated by the fact that three principal indices,  $\alpha$ ,  $\beta$  and  $\gamma$ , are to be determined.

*Measurement of the Angles of Refraction by Means of Prisms.* Two or three prisms must be used to determine the three indices. If three prisms are used they are cut so that their edges are parallel respectively to the *X*, *Y*, and *Z* directions of the mineral. In the case of an orthorhombic mineral, in which these directions are parallel to the directions of the three crystallographic axes, the prism edges would have to be respectively parallel to the *a*, *b*, and *c* crystal axes. In crystals of the monoclinic and triclinic systems the proper orientation of the three prisms is a matter of considerable difficulty.

Each such prism will yield two refracted and polarized rays but only the one whose light has its vibrations parallel to the edge of the prism (to be determined by the use of a nicol) is considered. In certain cases all three indices may be obtained from two prisms. If one prism is cut so that not only is its edge parallel to one of the directions  $X$ ,  $Y$ , and  $Z$  but so that its medial plane contains not only this direction but one other, then by the use of the method of minimum deviation an index may be determined from each of the two refracted rays. Or with a small angle prism cut so that one of its faces contains two of these directions the corresponding two indices may be determined when the method of perpendicular incidence is used upon this face. In making these measurements it is important to note the crystallographic directions parallel to which the different rays vibrate. In this way the optical orientation in respect to the crystallographic directions can be determined.

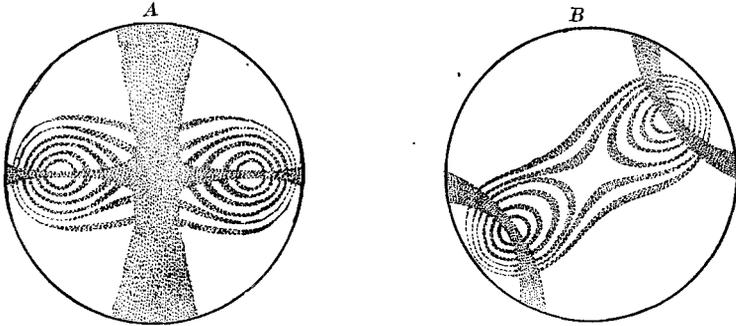
*Method of Total Reflection.* The method of total reflection for determining the indices of refraction of a biaxial mineral has the obvious advantage that only polished plates of the mineral are required instead of carefully orientated prisms. In general, the plane surface of a plate will give with the total refractometer two boundaries of total reflection. Both of these shadows move when the section is rotated. Four readings should be taken corresponding to the maximum and minimum positions of each boundary. The largest and smallest angles read will give on calculation the values for the greatest and least indices of refraction, *i.e.*,  $\gamma$  and  $\alpha$ . The mean index of refraction,  $\beta$ , can be derived from one of the other measurements. There are certain more or less complicated methods by which these two intermediate readings can be tested in order to prove which is the correct one for the index  $\beta$ . It is commonly simpler to make use of another plate having a different crystallographic orientation. It will be found that in the second plate one of the intermediate angles corresponds with one already observed on the first plate while the second angle shows no such correspondence. The angle that is common to the two plates is the one desired. If the plate is orientated so that its plane contains two of the three optical directions,  $X$ ,  $Y$  and  $Z$ , all three indices can be obtained easily from the single plate. In this case one of the boundaries of total reflection is stationary for different positions of the plate. This corresponds to the ray whose vibrations are normal to the surface of the plate. The other boundary will vary its position as the plate is rotated and yield at its maximum and minimum positions the angles corresponding to the other two indices of refraction.

**407. Sections of Biaxial Crystals in Convergent Polarized Light.** — In general, sections of biaxial crystals when examined in convergent polarized light show interference figures. The best and most symmetrical figures are to be observed when the section has been cut perpendicular to a bisectrix, and preferably to the acute bisectrix. If such a section is examined under the conditions described in the case of uniaxial crystals, see Art. 389, figures similar to those shown in Fig. 583 will be observed. When the axial plane, *i.e.*, the plane including the two optic axes, lies parallel to the direction of vibration of the polarizer the figure is similar to that of Fig. 583, A. When these two directions are inclined at a  $45^\circ$  angle the figure is like that shown in Fig. 583, B.

First consider the interference figure in the parallel position, Fig. 583, A and when viewed in monochromatic light. It consists of two black bars that form a cross somewhat similar to the cross of a uniaxial figure. The horizon-

tal bar is thinner and better defined than the vertical one. About two points on the horizontal bar, there will be observed a concentric series of dark elliptical curves which, as they enlarge, coalesce, forming first a figure eight and

583



Biaxial Interference Figures

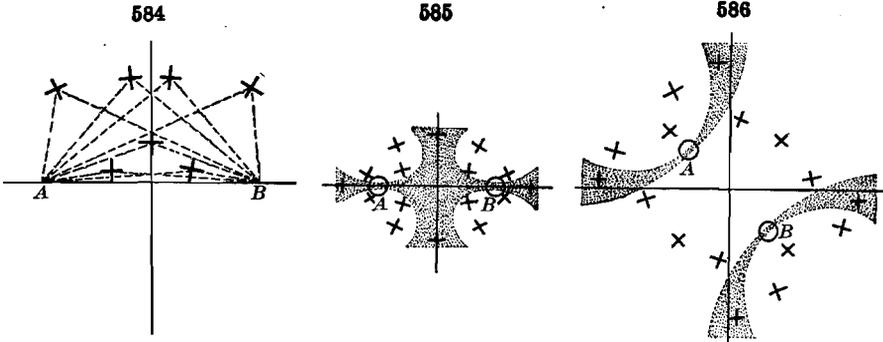
then a double curve. As the section is rotated on the microscope or polariscope stage, the black bars forming the cross separate at the center and curve across the field pivoting on these points until at the  $45^\circ$  position, Fig. 583, B, they form the two arms of a hyperbola.

A biaxial mineral has two directions, the directions of the optic axes, along which light travels with no double refraction. At these points there would be no birefringence and consequently dark spots would result. As the paths of the light rays become inclined to the directions of the optic axes the light suffers double refraction and in increasing degree as the amount of inclination becomes greater. Consequently at short distances away from these points the light must be refracted into two rays which have a difference of phase of one wave-length for a certain colored light, the yellow of the sodium flame in this case. The result will be extinguishment at such points. The assemblage of all points where the difference of phase equals one wave-length yields the first dark elliptical-like curve, called a lemniscate, shown in the figure. Further out will be found curves embracing the points where the difference of phase is two wave-lengths, three wave-lengths, etc.

If the interference figure is viewed in daylight instead of the monochromatic light the black curves will be replaced by colored ones. Each colored curve is produced by the elimination from the white light of some particular wave-length of light on account of the interference explained above.

The convergent bundle of light rays that pass through the section will each have its own particular plane of vibration. The directions of the planes of vibration for light emerging from the section at any given point can be found, as explained in Art. 397, by bisecting the angles made by two lines connecting this point with the two points of emergence of the optic axes. Fig. 584 shows how the direction of vibration of the two rays emerging from given points can be obtained in this way. These directions of vibration vary over the field and consequently some of them must always be parallel or very nearly so to the planes of vibration of the nicol prisms. When this happens the light is extinguished and darkness results. This explains the formation of the black bars of the interference figure. Fig. 585 shows the bars in the crossed position

and Fig. 586 when separated into the hyperbola arms. As the section is turned the vibration directions of new points successively become parallel to the planes of the nicols and so the dark bars sweep and curve across the field.



With a thick section or one of a mineral of high birefringence, the number of colored curves (when the figure is viewed in daylight) is greater than with a thinner section or one with low birefringence. An instructive experiment can be made by noting the changes in the interference figure obtained from a section of muscovite as the mineral is cleaved into thinner and thinner sheets. In most rock sections the minerals are ground so thin that their interference figures do not show any colored curves but rather only the dark hyperbola bars.

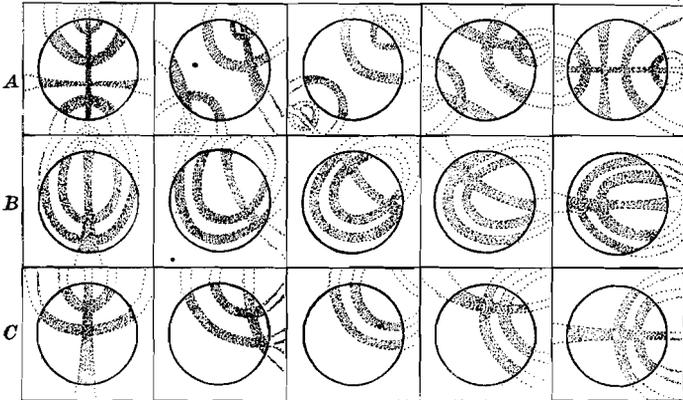
The biaxial interference figure varies in appearance with the change in the angle between the optic axes. Where this angle is very small the figure becomes practically the same as that of a uniaxial crystal. Where this angle becomes greater than  $60^\circ$  the points of the emergence of the optic axes will commonly lie outside the microscope field. In the latter case the hyperbola arms will appear as the section is brought into the parallel position, form a cross, and then as the section is further revolved will curve out of the field again. The larger the axial angle the more rapidly will the bars disappear from the field. A comparative measurement of the axial angles of two minerals can be made by noting the angle through which the microscope stage has to be turned in order to cause the bars to leave the field. The system of lenses must be kept the same for the two experiments. Or by experimenting with various minerals with known axial angles a scale could be derived for a certain microscope and system of lenses so that the axial angle of any other mineral could be approximately measured in this way.

A symmetrical interference figure may also be obtained from a section cut perpendicular to the obtuse bisectrix. In general, the obtuse axial angle is considerably larger than the acute angle and the interference figure will differ therefore in this respect from that obtained from the section cut perpendicular to the acute bisectrix.

It is important to be able to recognize the biaxial interference figures which are obtained from inclined sections. They are chiefly characterized by the fact that the hyperbola bars curve as they cross the field. This characteristic distinguishes the figure from an eccentric uniaxial figure in which the bars of the cross move in straight lines as the section is turned. Fig. 587 shows in the row A a series illustrating the appearance in different positions

of the figure when the section is slightly inclined to the bisectrix. In row *B*, a series where the section is cut perpendicular to an optic axis and the hyperbola bar revolves in the field as upon a pivot. In this case the bar curves

587



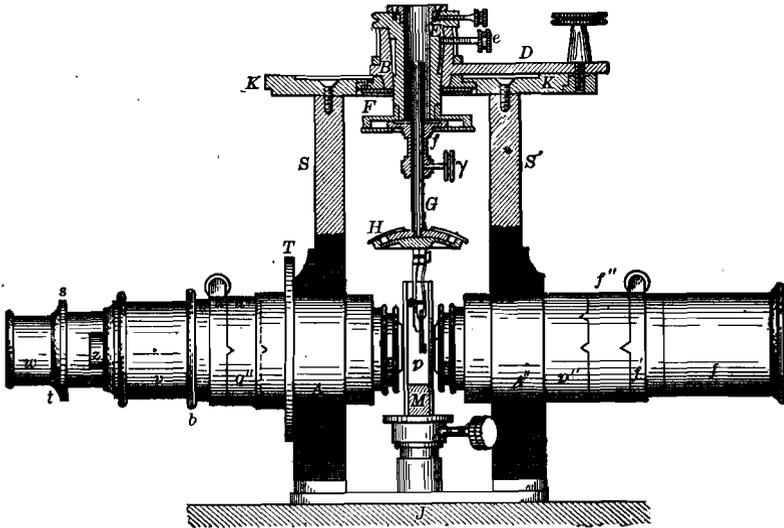
Eccentric Biaxial Interference Figures

with its convex side toward the acute bisectrix. If the axial angle was  $90^\circ$  there would be no distinction between acute and obtuse bisectrices and the bar would then revolve as a straight line. Therefore such a figure indicates by the amount of the curvature of the bar the size of the axial angle. The figures given by planes cut nearly normal to an optic axis are often of great use in the optical examination of a mineral. Sections which will furnish them are easily found by noting those sections of the mineral that remain dark or nearly so during their rotation between crossed nicols. If the single bar shown in such a figure exhibits a decided curvature it indicates that the direction of the acute bisectrix is not very much inclined to the plane of the section and consequently its character, whether *X* or *Z*, can be determined by noting the character of that extinction direction which symmetrically bisects the curve. From this observation the positive or negative character of the mineral can be determined. In row *C*, Fig. 587, is shown a series of figures where the section has a still greater inclination. A section cut parallel to the axial plane does not give a decisive interference figure. Often it is difficult to distinguish it from the figure obtained from a section cut parallel to the optic axis of a uniaxial mineral, see Art. 392. It should be pointed out that, while in general the interference figures of these two optical classes are to be clearly distinguished from each other, cases may arise in which such differentiation is difficult if not impossible.

**406. Measurement of the Axial Angle.** — The determination of the angle made by the optic axes is most accurately accomplished by use of the instrument shown in Fig. 588. The section of the crystal, cut at right angles to the bisectrix, is held in the pincers at *p*, with the plane of the axes horizontal, and making an angle of  $45^\circ$  with the vibration-plane of the nicols. There is a cross-wire in the focus of the eyepiece, and as the pincers holding the section are turned by the screw at the top (here omitted) one of the axes, that is, one black hyperbola, is brought in coincidence with the vertical cross-wire, and

then, by a further revolution, the second. The angle which the section has been turned from one axis to the second, as read off at the vernier on the graduated circle above, is the *apparent* angle for the axes of the given crystal

588



Axial Angle Apparatus

as seen in the air ( $aca = 2E$ , Fig. 589). It is only the *apparent* angle, for, on passing from the section of the crystal to the air, the true axial angle is more or less increased, according to the refractive power of the given crystal. The relation between the real interior angle and the measured angle is given below.

If the axial angle is large, the axes may suffer total reflection. In this case some oil or liquid with a high refractive power is interposed so that the axes will no longer be totally reflected but emerge into the liquid and thence into the air. In the instrument described a small receptacle holding the oil is brought between the tubes, as seen in the figure, and the pincers holding the section are immersed in this and the angle measured as before.

In the majority of cases it is only the acute axial angle that it is practicable to measure; but sometimes, especially when oil (or other liquid) is made use of, the obtuse angle can also be determined from a second section normal to the obtuse bisectrix.

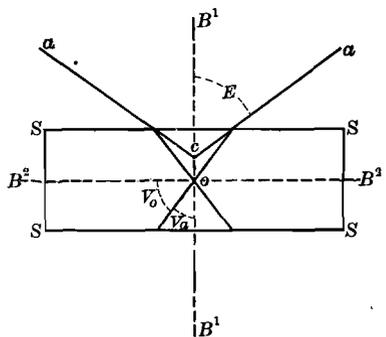
If  $E$  = the apparent semi-acute axial angle in air (Fig. 589),

$H_a$  = " " " " " in oil,

$H_o$  = " " semi-obtuse angle in oil,

$V_a$  = the (real or interior) semi-acute angle,

589



Measurement of Axial Angle

$V_o$  = the (real or interior) semi-obtuse angle,

$n$  = refractive index for the oil or other medium,

$\beta$  = the mean refractive index for the given crystallized substance,

the following simple relations connect the various quantities mentioned:

$$\sin E = \beta \sin V_a; \sin E = n \sin H_a; \sin V_a = \frac{n}{\beta} \sin H_a; \sin V_o = \frac{n}{\beta} \sin H_o.$$

These formulas give the true interior angle ( $2V$ ) from the measured apparent angle in air ( $2E$ ) or in oil ( $2H$ ) when the mean refractive index ( $\beta$ ) is known.

**409. Axial Angle Measured with the Microscope.** — Approximate measurements of the axial angle may be made by various methods with the microscope. In most cases some sort of a micrometer ocular is used which contains an engraved scale. By means of this scale the distance between the points of emergence of the optic axes can be determined. Mallard\* showed that the distance of any point from the center of the interference figure as observed in the microscope is very closely the same as the sine of the angle which the ray emerging at this point makes with the axis of the microscope. The Mallard equation for the derivation of the axial angle is  $D = K \sin E$ , in which  $D$  equals one half the measured distance between the optic axes and  $K$  a constant which varies with the microscope and the system of lenses used.  $K$  for a given set of lenses may be determined by observing the interference figures derived from plates of minerals with known axial angles and then substituting the values for  $D$  and  $E$  in the above equation. The angular values of the divisions on the micrometer scale of the ocular may also be determined directly by the use of an instrument known as the apertometer. The measurement of an axial angle by means of the microscope is naturally most easily accomplished when the points of emergence of both optic axes are visible in the field. It is possible, however, by various ingenious methods to determine its value when only one optic axis is in view. These methods are too complicated and too seldom used to be explained here and the reader is referred to the text books on the methods of petrographic investigation for their details.†

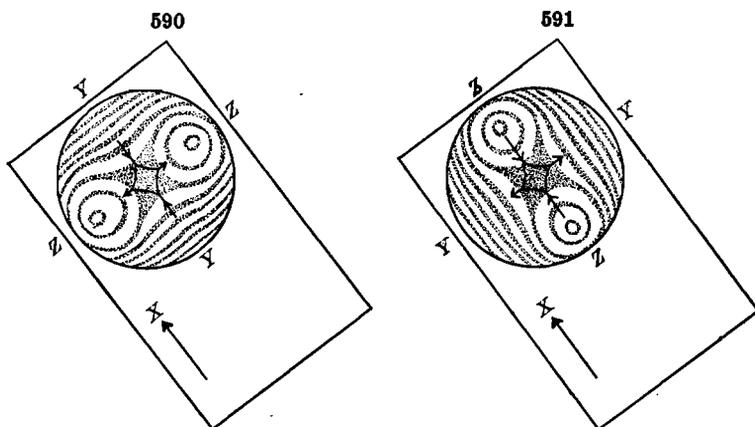
**410. Determination of the Optical Character of a Biaxial Mineral from Its Interference Figure. Use of the Quartz Wedge.** — If the section is turned until its interference figure is in the  $45^\circ$  position and then the quartz wedge inserted above the section through the  $45^\circ$  slot in the microscope tube the vibration directions of the section along a line that joins the optical axes and a line at right angles to this through the center of the figure will be parallel to the vibration directions of the quartz-wedge. Under these circumstances the effect of the introduction of the quartz wedge will be to gradually increase or diminish along these lines the birefringence due to the section alone. If the directions of vibration of the faster and slower rays in the quartz coincide with the vibration directions of the similar rays in the section, the total birefringence will be increased and the effect upon the interference figure will be as if the section had been thickened. Complete interference will take place with rays of less obliquity and the colored curves will be drawn closer together. They will move, as the quartz wedge is pushed in over the section, as indicated by the arrows shown in Fig. 590. On the other hand, if the quartz wedge is so placed that its optical orientation is opposed to that of the section, the effect will be the same as if the section was being gradually thinned. The colored rings about the points of the optic axes will expand until they meet in the center as a figure eight and then grow outwards as a continuous curve. The directions of their movements are shown by the arrows in Fig. 591. Therefore, by knowing the optical orientation of the quartz-wedge and noting the

\* Bull. Soc. Min., 5, 7787, 1882.

† See especially Wright, The Methods of Petrographic Microscopic Research, and Johanssen, Manual of Petrographic Methods.

effect of its introduction over a section upon the interference figure, it is possible to determine the relative character of the two important extinction directions of the sections; that is, to determine whether the ray vibrating in the plane which includes the optic axes is faster or slower than the one which vibrates in the plane at right angles to this direction.

In the case of a positive mineral the acute bisectrix, which in a symmetrical interference figure is the direction normal to the section, is the direction  $Z$ . Consequently the direction of the line in the section which passes through the points of emergence of the two optic axes is the direction of the obtuse bisectrix, or in this case the direction  $X$ . The direction  $Y$  then will lie in the plane of the section and at right angles to the line joining the points of emergence of the optic axes. In the case, therefore, of a positive



Determination of Optical Character of Biaxial Mineral with Quartz Wedge

mineral, the faster ray has its vibrations lying in the optical axial plane. With a negative mineral the direction  $X$  becomes the acute bisectrix and will be normal to the section, while the direction  $Z$  will lie in the section along the line connecting the points of emergence of the optic axes. With a negative mineral, therefore, the vibration direction which lies in the optical axial plane is of the slower ray. By finding, therefore, the relative character of these two vibration directions the optical character of the mineral is determined. The effects produced by an interference figure which is perpendicular to an obtuse bisectrix would be exactly opposite to those described above. It is imperative, therefore, that the positions of the two bisectrices be definitely known. With sections that are very thin or with minerals of low birefringence the interference figure may show only the black hyperbolas without any colored rings. In such cases, frequently the introduction of the quartz wedge in such a position that its optical orientation is parallel to that of the section will suffice to so thicken the section in effect as to cause the appearance of colored rings. Further, with such sections it is possible to establish the directions in the section that are parallel and at right angles to the trace upon the section of the optical axial plane. Then, by use of the sensitive tint, when the convergent lens has been removed the character of the vibrations parallel to these two directions is easily determined.

**411. Absorption Phenomena of Biaxial Crystals. Pleochroism.**—

Colored biaxial crystals like similar uniaxial crystals may show different degrees or kinds of absorption of the light passing through them depending upon the direction of vibration of the light. In biaxial crystals there may be three different degrees of absorption corresponding to three different directions of vibration lying at right angles to each other. In general, these directions coincide with the optical directions  $X$ ,  $Y$ , and  $Z$ . Variations from this parallelism may be observed, however, in crystals of the monoclinic and triclinic systems. It is customary, however, to describe the absorption as it is observed parallel to the directions  $X$ ,  $Y$ , and  $Z$ . If light vibrating parallel to  $X$  is the most absorbed and light vibrating parallel to  $Z$  is the least absorbed these facts are expressed as  $X > Y > Z$ . There are various other possibilities, such as  $X > Y = Z$ ,  $Z > X > Y$ , etc. Further, according to the kind of selective absorption, the crystal may show distinctly different colors for light vibrating in the different directions, or in general show *pleochroism*. The character of the pleochroism is stated by giving the colors corresponding to the vibrations parallel to  $X$ ,  $Y$ , and  $Z$ . For instance, in the case of *riebeckite*,  $X$  = deep blue,  $Y$  = light blue,  $Z$  = yellow-green. In order to investigate the absorption properties of a biaxial crystal at least two sections must be obtained in which will lie the directions  $X$ ,  $Y$ , and  $Z$ . These sections are examined on the stage of the polariscope or microscope without the upper nicol. They will show as they are rotated upon the stage variations in absorption and in color as the light passing through them vibrates parallel to first one and then the other of their vibration directions. See the discussion of dichroism in uniaxial minerals, Art. 393.

When a section cut normal to an optic axis of a crystal characterized by a high degree of color-absorption is examined by the eye alone (or with the microscope) in strongly converging light, it often shows the so-called *epoptic figures*, *polarization-brushes*, or *houppes* somewhat resembling the ordinary axial interference-figures. This is true of andalusite, epidote, iolite, also tourmaline, etc. A cleavage section of epidote  $\parallel c(001)$  held close to the eye and looked through to a bright sky shows the polarization-brushes, here brown on a green ground. These figures are caused by the light being differently absorbed as it passes through the section with different degrees of inclination.

In certain minerals small circular or elliptical spots may be observed in which the pleochroism is stronger than in the surrounding mineral. These are commonly spoken of as *pleochroic halos*. They are found to surround minute inclusions of some other mineral. There have been many diverse theories to account for these "halos" but recently it has been shown that they are probably due to some radioactive property of the inclosed crystal. Pleochroic halos have been observed in biotite, iolite, andalusite, pyroxene, hornblende, tourmaline, etc., while the included crystals belong to allanite, rutile, titanite, zircon, apatite, etc.

*Special Optical Characters of Orthorhombic Crystals*

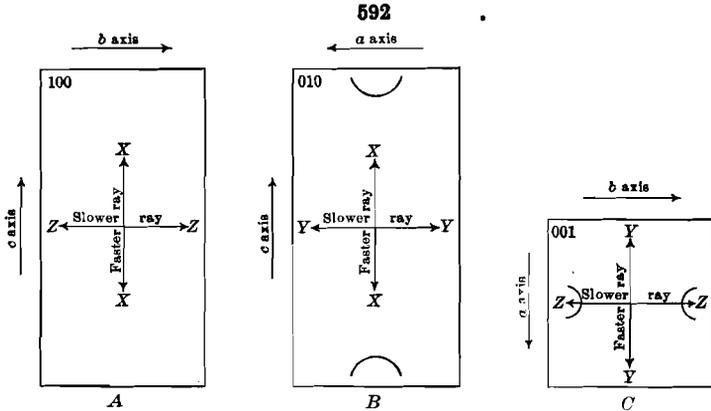
**412. Position of the Ether-axis.**— In the ORTHORHOMBIC SYSTEM, in accordance with the symmetry of the crystallization, the three axes of the indicatrix, that is, the directions  $X$ ,  $Y$ , and  $Z$ , *coincide* with the three crystallographic axes, and the three crystallographic axial planes of symmetry correspond to the planes of symmetry of the ellipsoid. Further than this, there is no immediate relation between the two sets of axes in respect to magnitude, for the reason that, as has been stated, the choice of the crystallographic axes is arbitrary so far as relative length and position are concerned, and hence made, in most cases, without reference to the optical character.

Sections of an orthorhombic crystal parallel to a pinacoid plane ( $a(100)$ ,  $b(010)$ , or  $c(001)$ ) appear dark between crossed nicols, when the axial directions

coincide with the vibration-planes of the nicols; in other words, such sections show parallel extinction.

The same is true of all sections that are parallel to one of the three crystallographic axes, *i.e.*, sections lying in the prism, macrodome and brachydome zones. Sections, however, that are inclined to all three crystallographic axes, *i.e.*, pyramidal sections, will show inclined extinction.

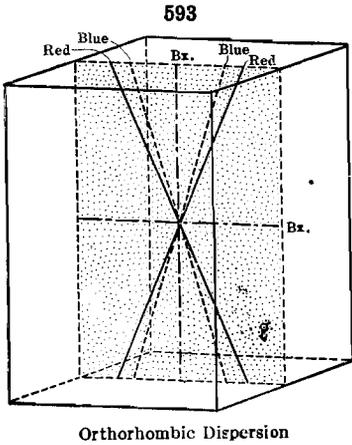
**413. Determination of the Plane of the Optic Axes.** — The plane of the *optic axes*, that is, the plane including the directions *X* and *Z*, must be parallel to one of the three pinacoids. Further, the acute bisectrix must be normal to one of the two pinacoids that are at right angles to the optic axial plane while the obtuse bisectrix is normal to the other such pinacoid. The optical orientation, *i.e.*, the relation between the principal optical and crystallographic directions, can be easily determined by the examination of sections of a crystal which are cut parallel to the three pinacoids. To illustrate by an example, let it be assumed that such sections of the mineral aragonite are available. These are represented in Fig. 592, *A*, *B*, and *C*. If the relative



Optical Orientation of Aragonite

characters of the vibration directions of each section are determined it will be found that light vibrating parallel to the *c* axis in sections parallel to (100) and (010) is in both cases moving with the greater velocity, that light vibrating parallel to the *b* axis in (100) and (001) is in both cases the slower ray, and that light vibrating parallel to the *a* axis is the faster ray in (001) but the slower ray in (010). From this it is seen that the *a* axis must coincide with the direction of vibration of the ray having the intermediate velocity, or be the same as the optical direction *Y*. Also it follows that *c* axis = *X* and *b* axis = *Z*. The optic axial plane, therefore, since it must include *X* and *Z*, lies parallel to (100). If the sections parallel to (001) and (010) are examined in convergent light both will show biaxial interference figures with the points of emergence of the optic axes lying as illustrated in *B* and *C*, Fig. 592. The axial angle observed with the section parallel to (001) is much smaller than that obtained from (010). Consequently the acute bisectrix is normal to the base (001) and since it is the direction *X* the mineral is optically negative. These facts of optical orientation may be summarized in the statements: optically —, Ax. pl. || *a*(100), Bx<sub>a</sub> ⊥ *c*(001).

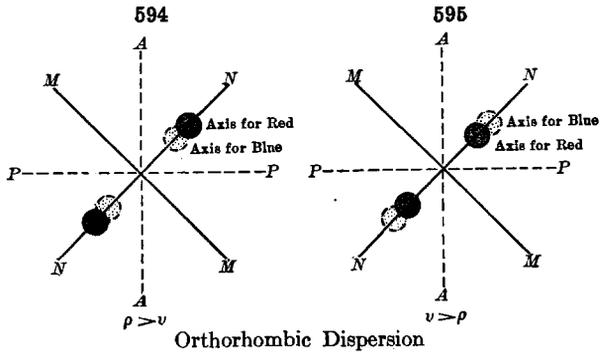
**414. Dispersion of the Optic Axes in Orthorhombic Crystals.** — In determining the indices of refraction of a crystal by means of the prism method it is to be noted that when the incident ray is of white light the refracted ray will in general show this white light dispersed into its primary colors. The amount of this dispersion is usually small but in certain substances becomes considerable. Obviously since the angle of refraction varies in this way with the different wave-lengths of light the indices of refraction will also vary. In biaxial minerals, as already stated, the optic axial angle is directly dependent upon the relative values of the three indices of refraction,  $\alpha$ ,  $\beta$ , and  $\gamma$ . As these indices may show considerable differences, depending upon the



wave-length of the refracted ray, it follows that the optic axial angle will also vary with the color of the light used. In other words, the optic axes may be dispersed. Fig. 593 represents such a case in which the angle between the optic axes for red light is greater than that for blue. The opposite condition may hold, in which the angle for blue is greater than for red. From this it follows that the interference figure when observed in blue light will not exactly coincide with that produced by red light. The bisectrices of both figures will be the same but the position of the points where the optic axes emerge will be different and consequently the positions of the hyperbolas and lemniscate curves will also be different. In the case of orthorhombic

crystals the dispersion will always be symmetrical to the two symmetry planes of the indicatrix that pass through the acute bisectrix, *i.e.*, the directions  $M-M$  and  $N-N$  in Figs. 594 and 595.

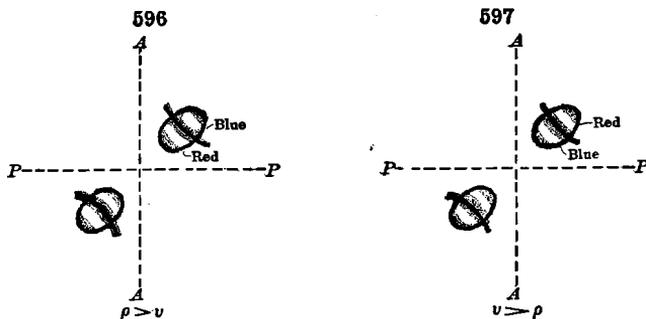
This particular type of dispersion is said to be *Orthorhombic Dispersion*, in order to distinguish it from that observed in biaxial crystals of other systems. The two possible cases of orthorhombic dispersion are shown in Figs. 594 and 595. In expressing these two cases the Greek letters  $\rho$  (for red) and  $\nu$  (for violet) are used. When the axes for red light are more dispersed than those for blue that fact is expressed as  $\rho > \nu$  or in the reverse case it is  $\rho < \nu$ .



When the axes for red light are more dispersed than those for blue that fact is expressed as  $\rho > \nu$  or in the reverse case it is  $\rho < \nu$ .

In the majority of cases the effect produced upon the interference figure by the dispersion of the optic axes is too slight to be noted. In exceptional cases where the amount of dispersion is large the effects are clearly seen. The hyperbola bars, which are ordinarily black throughout, will, when the figure

is observed in white light, be seen, near the center, to be bordered on one side by a red fringe and on the other by a blue one. The first one or two of the colored lemniscates will also be broadened out along the line joining the two optic axes. As already stated these changes in the appearance of the figure will always be symmetrical in respect to the traces of the two symmetry planes



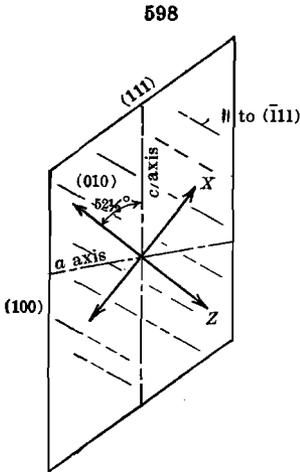
Orthorhombic Dispersion

lying at right angles to each other. In the case, Fig. 594, where the axes for red light are farther apart than those for blue ( $\rho > \nu$ ), the hyperbolas in the interference figure for the two different wave-lengths of light will not coincide and the ones where the red light is extinguished will be farther out than those for blue light. When red light is taken out of the white light, blue remains, and conversely when blue is subtracted the resultant color is red. Consequently in this case the hyperbola bars will be bordered on their concave sides by blue and on their convex sides by red, Fig. 596. In the other case, where  $\rho < \nu$ , the hyperbolas will be bordered on their concave sides by red and on their convex sides by blue, Fig. 597. In other words, if blue light shows at the larger angle it means that red light has been eliminated from these positions and the optic axes for red are more dispersed than those for blue, etc.

*Special Optical Characters of Monoclinic Crystals*

**415. Optical Orientation of Monoclinic Crystals.** — In monoclinic crystals there is one axis of symmetry, the *b* crystallographic axis, and one plane of symmetry, the plane of the *a* and *c* crystallographic axes. These are the only crystallographic elements that are definitely fixed in position. One of the three chief optical directions, *X*, *Y*, or *Z*, is coincident with the *b* crystallographic axis, while the other two lie in the symmetry plane, (010), but not parallel to any crystal direction. There are obviously three possible cases. If *Y* coincides with the axis *b* (and this is apparently the most common case) the directions *X* and *Z* will lie in the crystal symmetry plane, which therefore becomes the optic axial plane. If *X* or *Z* coincides with the *b* axis the optic axial plane will be at right angles to (010) and either the acute or obtuse bisectrix will be normal to that plane. This clino-pinacoid of a monoclinic crystal is usually the best plane upon which to study its optical orientation. Fig. 598 represents such a section cleaved from an ordinary crystal of gypsum. The cleavages parallel to (100) and ( $\bar{1}11$ ) will serve to give its crystallographic orientation. Examination of the section in convergent light fails to show a distinct interference figure, consequently it is to be assumed that the section itself is parallel to the optic axial plane and that the direction *Y* is

normal to the section. When the section is rotated on the microscope stage between crossed nicols its extinction directions are seen to be inclined to the direction of the *c* crystallographic axis, the angle of inclination being measured as  $52\frac{1}{2}^\circ$ . The relative character of the two extinction directions can be



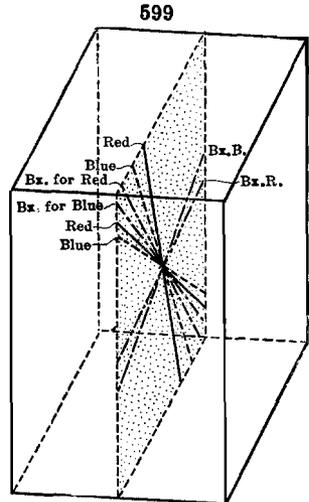
Optical Orientation of Gypsum

easily determined by the use of the quartz wedge and so the position of *X* and *Z* established. In this way the orientation of the *X*, *Y* and *Z* directions can be determined. It is also possible from this section to determine whether the mineral is optically positive or negative. If the section is viewed in convergent light a somewhat vague interference figure is observed. When the section is turned from its position of extinction it will be noted that faint dark hyperbolas rapidly move out of the field. Careful observation will show that they disappear more slowly into one set of quadrants than into the other. The line bisecting the opposite quadrants into which the hyperbola bars disappear more slowly is the direction of the acute bisectrix. The *X* or *Z* character of this direction can be determined and from this the positive or negative character of the mineral. In a similar way the clino-pinacoid section of crystals belonging to the two other possible classes would

yield data concerning their optical orientations.

**416. Extinction in Monoclinic Crystals.** — Since only one of the three principal optical directions, *X*, *Y*, or *Z*, of a monoclinic crystal coincides with a crystallographic axis, namely the symmetry axis *b*, it follows that only sections that are parallel to this axis, *i.e.*, sections in the orthodome zone, will show parallel extinction. All other sections will exhibit inclined extinction.

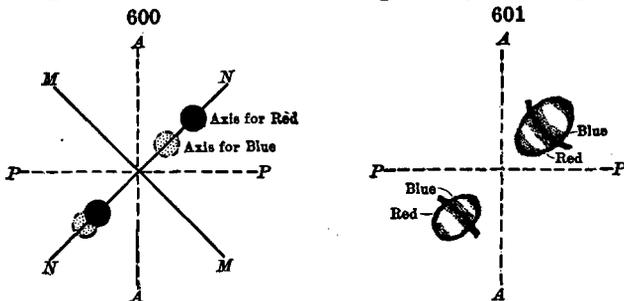
**417. Dispersion in Monoclinic Crystals.** — As previously stated there are three possible optical orientations of a monoclinic crystal. In the first case the vibration direction *Y* coincides with that of the symmetry axis *b* and the optic axial plane coincides with the symmetry plane (010). In the other cases either the vibration direction *X* or *Z* coincides with the crystallographic axis *b* and the optic axial plane is at right angles to the crystallographic symmetry plane. Under these conditions either the acute or obtuse bisectrix may coincide with the axis *b*. Each of these three possibilities may produce a different kind of dispersion. It should be emphasized that the phenomenon of dispersion is seldom to be clearly observed and then commonly only in unusually thick mineral sections.



Inclined Dispersion

**Case 1. Inclined Dispersion.** Inclined dispersion is observed in the case

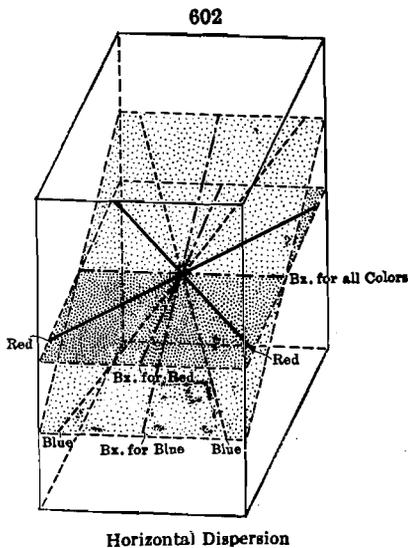
where the direction  $Y$  coincides with the axis  $b$ . This is illustrated in Fig. 599. In this case not only may the axial angles vary for light of different wave-lengths but the bisectrices of these angles may lie along different lines.



Inclined Dispersion,  $\rho > \nu$

So, here, both the optical axes and the bisectrices may be dispersed. In Fig. 599 with  $\rho > \nu$  the angle between the optic axes for red light is greater than that for blue. But because of the dispersion of the bisectrices it follows that on one side the point of emergence of the optic axis for red light lies beyond that for blue, while on the other side the conditions are reversed. Also the optic axes for red and blue will be farther apart on one side of the interference figure than on the other side. With this sort of dispersion the interference figure will be symmetrical only in respect to the line which is the trace upon the section of the optic axial plane,  $N-N$ , Fig. 600, but is unsymmetrical to the line at right angles to it,  $M-M$ .

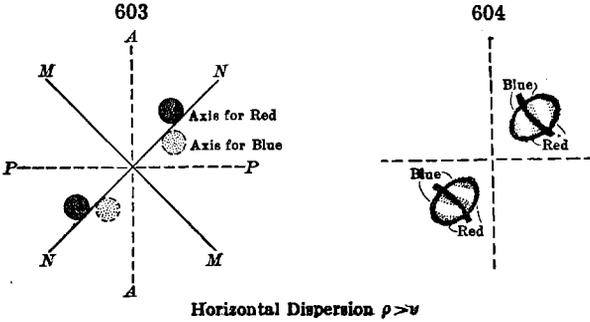
Inclined dispersion is shown in the interference figure by the fact that the colored borders to the hyperbola bars are reversed in the two cases, *i.e.*, if blue is on the concave side of one, red will be on the concave side of the other. Further, the amount of dispersion shown is much greater with one bar than with the other. Fig. 601 represents a case of inclined dispersion.



Horizontal Dispersion

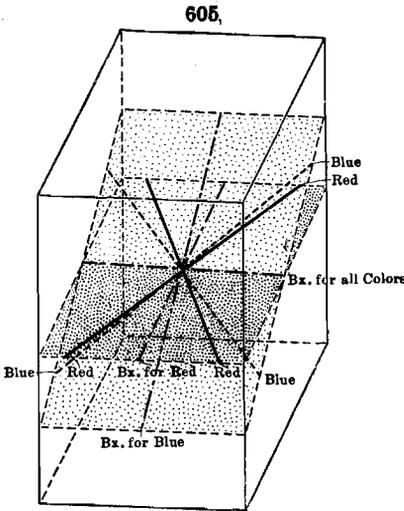
Case 2. *Horizontal Dispersion.* In this case the crystallographic axis  $b$  coincides with the obtuse bisectrix which may be either the  $X$  or  $Z$  direction, depending upon whether the crystal is optically positive or negative in character. In this case the direction of the obtuse bisectrix is fixed for light of all wave-lengths. The angle between the optic axes may vary and further the position of the acute bisectrix may vary as long as it lies in the crystallographic symmetry plane. In other words, the axial planes may be dispersed, see Fig. 602. The points of emergence of the optic axes, when  $\rho > \nu$ , for blue and red light, might therefore be like that shown in Fig. 603. It will be noted that in this case the interference figure (obtained of course from a section approx-

imately perpendicular to the acute bisectrix) is symmetrical to the line  $M-M$  but unsymmetrical in respect to the line  $N-N$ . Fig. 604 shows the effect of horizontal dispersion upon the interference figure.



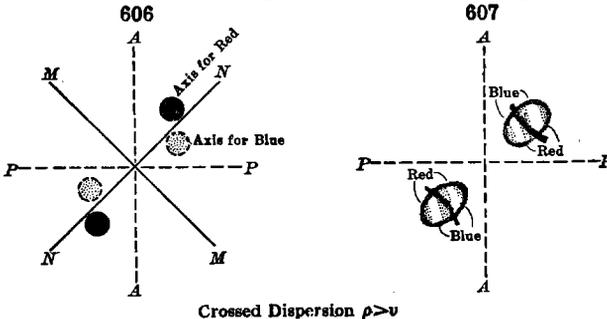
Case 3. *Crossed Dispersion.*

In this case the crystallographic axis  $b$  coincides with the acute bisectrix, which may be either the  $X$  or  $Z$  direction depending upon the optical character of the crystal. In this case the direction of the acute bisectrix is fixed for light of all wave-lengths. The angle between the optic axes may vary and further the position of the axial planes for different wave-lengths may vary as long as they remain perpendicular to the crystallographic symmetry plane. A case of this sort is shown in Fig. 605. The points of emergence of the optic axes when  $\rho > \nu$  for blue and red light might therefore be like that shown in Fig. 606. It will be seen that in this case the figure is symmetrical to neither the line  $M-M$  nor  $N-N$  but only to the central point of the figure, *i.e.*, the point of emergence of the acute bisectrix. Fig. 607 shows



Crossed Dispersion

the effect of crossed dispersion upon the interference figure.



*Special Optical Characters of Triclinic Crystals*

**418. Optical Orientation of Triclinic Crystals.** — The center of the optical ellipsoidal figure coincides with the center of the system of crystallographic axes but there is no further correspondence between optical and crystallographic directions.

**419. Extinction in Triclinic Crystals.** — Since there is no parallel relation existing between optical and crystallographic directions in triclinic crystals all sections will show inclined extinction.

**420. Dispersion in Triclinic Crystals.** — Because of the lack of coincidence between any optical and crystallographic direction in triclinic crystals it follows that the optic axes and bisectrices for different wave-lengths of light may be dispersed in any direction. Consequently the dispersion shown in an interference figure obtained from a triclinic crystal is irregular and without symmetry.

**421. Suggestions as to Methods and Order of Optical Tests upon an Unknown Mineral.** — *Preparation of Material.* The size and character of the fragments or section of a mineral to be studied will depend upon various circumstances. In the majority of cases it will probably be most convenient to crush the mineral into small uniform sized fragments. In other cases a cleavage flake of the mineral will serve, and under still other conditions it may be preferable to cut an unorientated or, better, an orientated section. For at least the preliminary examination small irregular fragments of varying orientation will most often be used. Take a few of these mineral grains and place them upon an object glass and immerse them either in Canada balsam or in some oil with known refractive index and cover with a piece of thin cover glass. In the majority of cases it will prove more expeditious and convenient to place the fragments in an oil.

*Order of Optical Tests.* Below is given a brief outline of the natural order of observations and tests to be made upon the mineral.

1. *Observations in plane polarized light without the upper nicol.*
  - a. Note color of mineral, whether uniform or not.
  - b. By rotating slide on microscope stage test for possible pleochroism. If the mineral exhibits pleochroism it cannot be isotropic. Connect as far as possible the directions of absorption with crystallographic directions.
  - c. Note crystal outline, if any; cleavage cracks, etc.
  - d. Note any inclusions, their shape and arrangement.
  - e. Index of refraction. Determine approximately the refractive index. Note character of relief and determine whether mineral has a higher or lower index than the medium in which it is immersed (see Art. 325).
2. *Observations in plane polarized light with crossed nicols.*
  - a. If the section is dark between crossed nicols and remains so during the rotation of the stage the mineral is either isotropic or orientated perpendicular to an optic axis. In the latter case test as indicated below under 3a.
  - b. If the section is alternately light and dark during the rotation of the stage the mineral is anisotropic.
  - c. Note position of extinction directions. If they are inclined to some known crystallographic direction measure the angle of inclination.

- d. Determine the relative character of the two vibration directions of the section (*i.e.*, the two extinction directions), as to which corresponds to the faster and which to the slower ray. Test to be made with quartz wedge or sensitive tint, see Art. 348.
  - e. Find the grain showing the highest order of interference color and so approximately determine the strength of the mineral's birefringence.
  - f. By immersion in oils of known refractive indices determine as accurately as possible the range of the refractive indices shown by the mineral. It may be possible in connection with tests made under 3 to determine the values for certain of the principal refractive indices.
3. *Observations in convergent polarized light with crossed nicols.*
- a. Note whether the mineral shows an interference figure, and if so whether it is uniaxial or biaxial.
  - b. If mineral is uniaxial determine the position of the optic axis in respect to the plane of the given section and if possible determine the positive or negative character of the mineral.
  - c. If the mineral is biaxial determine the position of the axial plane in respect to the section. Determine, if possible, the positive or negative character of the mineral. Obtain, if possible, an approximate idea as to the size of the axial angle. Note any evidences of dispersion.

*Note.* — In making the above tests it is helpful to keep, as far as possible, a graphic record of the results, something like that illustrated in Fig. 592.

**422. Effect of Heat upon Optical Characters.** — The general effects of heat upon crystals as regards expansion, etc., are spoken of later. It is convenient, however, to consider here, briefly, the changes produced by this means in the special optical characters. It is assumed that no alteration of the chemical composition takes place and no abnormal change in molecular structure. In general, the effect of a temperature change causes a change in the refractive indices. In the majority of cases the indices decrease in value with rise of temperature but in certain cases the reverse is true. It is consequently important in any exact statement of a refractive index to give the temperature at which it was determined. The particular facts for the different optical classes are as follows:

(1) *Isotropic* crystals remain isotropic at all temperatures. Crystals, however, which, like sodium chlorate ( $\text{NaClO}_3$  of Class 5, p. 72), show circular polarization may have their rotatory power altered; in this substance it is increased by rise of temperature.

(2) *Uniaxial* crystals similarly remain uniaxial with rise or fall of temperature; the only change noted is a variation in the relative values of  $\omega$  and  $\epsilon$ , that is, in the strength of the double refraction. This increases, for example, with calcite and grows weaker with beryl and quartz. It is, further, interesting to note that the rotatory power of quartz increases with rise of temperature, but the relation for all parts of the spectrum remains sensibly the same.

(3) With *Biaxial* crystals, the effect of change of temperature varies with the system to which they belong.

The axial angle of biaxial crystals may be measured at any required temperature by the use of a metal air-bath. This is placed at *P* (Fig. 538) and extends beyond the instrument on either side, so as to allow of its being heated with gas-burners; a thermometer inserted

in the bath makes it possible to regulate the temperature as may be desired. This bath has two openings, closed with glass plates, corresponding to the two tubes carrying the lenses, and the crystal-section, held as usual in the pincers, is seen through these glass windows. Suitable accessories to the refractometer also allow of the measurement of the refractive indices at different temperatures.

In the case of *orthorhombic* crystals, the position of the three rectangular ether-axes cannot alter, since they must always coincide with the crystallographic axes. The values of the refractive indices, however, may change, and hence with them also the optic axial angle; indeed a change of axial plane or of the optical character is thus possible.

With *monoclinic* crystals, one ether-axis must coincide at all temperatures with the axis of symmetry, but the position of the other two in the plane of symmetry may alter, and this, with the possible change in the value of the refractive indices, may cause a variation in the degree (or kind) of dispersion as well as in the axial angle.

With *triclinic* crystals, both the positions of the ether-axes and the values of the refractive indices may change. The observed optical characters may therefore vary widely.

A striking example of the change of optical characters with change of temperature is furnished by gypsum, as investigated by Des Cloizeaux. At ordinary temperatures, the dispersion is inclined, the optic axial plane is  $\parallel b(010)$  and  $2E_r = 95^\circ$ . As the temperature rises this angle diminishes; thus, at  $47^\circ$ ,  $2E_r = 76^\circ$ ; at  $95^\circ$ ,  $2E_r = 39^\circ$ ; and at  $116^\circ$ ,  $2E_r = 0$ . At this last temperature the axes for blue rays have already separated in a plane  $\perp b(010)$ ; at  $120^\circ$  the axes for red rays also separate in this plane ( $\perp b$ ) and the dispersion becomes *horizontal*. The motion toward the center of one red axis is more rapid than that of the other, namely, between  $20^\circ$  and  $95^\circ$ , one axis moves  $33^\circ 55'$  while the other moves only  $22^\circ 38'$ ; thus  $Bx_r$  moves  $5^\circ 38'$ .

Another interesting case is that of glauberite. Its optical characters under normal conditions are described as follows: Optically —. Ax. pl.  $\perp b(010)$ ,  $Bx_{a,r} \wedge c$  axis =  $-31^\circ 3'$ ,  $Bx_{a,y} \wedge c$  axis =  $-30^\circ 46'$ ,  $Bx_{a,b} \wedge c$  axis =  $-30^\circ 10'$ . The optical character (—) and the position of the axes of elasticity remain sensibly constant between  $0^\circ$  and  $100^\circ$ . The ax. pl., however, at first  $\perp b(010)$  with horizontal dispersion and  $\nu < \rho$  becomes on rise of temperature  $\parallel b$  with inclined dispersion and  $\nu > \rho$ . The axial angle accordingly diminishes to  $0^\circ$  at a temperature depending upon the wave-length and then increases in the new plane. In white light, therefore, the interference-figures are abnormal and change with rise in temperature.

Des Cloizeaux found that the feldspars, when heated up to a certain point, suffer a change in the position of the axes, and if the heat becomes greater and is long continued they do not return again to their original position, but remain altered.

In addition to the typical cases referred to, it is to be noted that when elevation of temperature is connected with change of chemical composition wide changes in optical characters are possible. This is illustrated by the zeolites and related species, where the effect of loss of water has been particularly investigated.

Further, with some crystals, heat serves to bring about a change of molecular structure and with that a total change of optical characters. For example, the greenish-yellow (artificial) orthorhombic crystals of antimony iodide ( $SbI_3$ ) on heating (to about  $114^\circ$ ) change to red uniaxial hexagonal crystals. Note also the remarks made later in regard to the effect of heat upon leucite and boracite (Art. 429).

**423. Some Peculiarities in Axial Interference-figures.\*** — In the case of uniaxial crystals, the characteristic interference-figure varies but little from one species to another, such

\* Variations in the axial figures embraced under the head of optical anomalies are spoken of later (Art. 429).

variation as is observed being usually due to the thickness of the section and the birefringence. In some cases, however, peculiarities are noted. For example, the interference-figure of apophyllite is somewhat peculiar, since its birefringence is very weak, and it may be optically positive for one part of the spectrum and negative for the other.

In the case of biaxial crystals, peculiarities are more common. The following are some typical examples:

Brookite is optically + and the acute bisectrix is always normal to  $a(100)$ . While, however, the axial plane is  $\parallel c(001)$  for red and yellow, with  $2E_r = 55^\circ$ ,  $2E_y = 30^\circ$ , it is commonly  $\parallel b(010)$  for green and blue, with  $2E_{gr} = 34^\circ$ . Hence a section  $\parallel a(100)$  in the microscope shows a figure somewhat resembling that of a uniaxial crystal but with four sets of hyperbolic bands.

Titanite also gives a peculiar interference-figure with colored hyperbolas because of the high color-dispersion,  $\rho > v$ , the variation between  $2E$  for red and green light being approximately  $10^\circ$ ; the dispersion of the bisectrices is, however, very small.

The most striking cases of peculiar axial figures are afforded by twin crystals (Art. 425).

**424. Relation of Optical Properties to Chemical Composition.** — The effect of varying chemical composition upon the optical characters has been minutely studied in the case of many series of isomorphous salts, and with important results. It is, indeed, only a part of the general subject of the relation between crystalline form and molecular structure on the one hand and chemical composition on the other, one part of which has been discussed in Art. 322. It was shown there that the refractive index can often be approximately calculated from the chemical composition.

Among minerals, the most important examples of the relation between composition and optical characters are afforded by the triclinic feldspars of the albite-anorthite series. Here, as explained in detail in the descriptive part of this work, the relation is so close that the composition of any intermediate member of this isomorphous group can be predicted from the position of its ether-axes, or more simply from the vibration directions on the fundamental cleavage-directions,  $\parallel c(001)$  and  $\parallel b(010)$ .

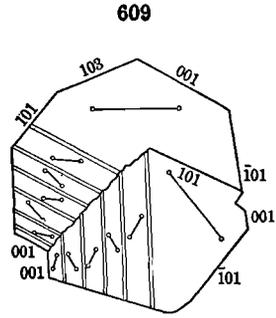
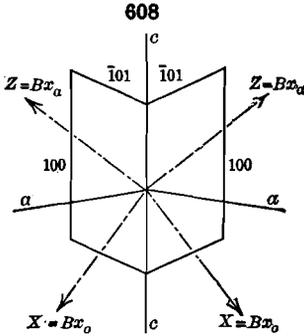
The effect of varying amounts of iron protoxide (FeO) is illustrated in the case of the monoclinic pyroxenes, where, for example, the angle  $Bx_a \wedge c$  axis is  $38^\circ$  in diopside (2.9 p. c. FeO) and  $47^\circ$  in hedenbergite (26 p. c. FeO). This is also shown in the closely related orthorhombic species of the same group, enstatite,  $MgSiO_3$  with little iron, and hypersthene,  $(Mg, Fe)SiO_3$  with iron to nearly 30 p. c. With both of these species the axial plane is parallel to  $b(010)$ , but the former is optically + ( $Bx_a = Z$ ) and the dispersion  $\rho < v$ ; the latter is optically - ( $Bx_a = X$ ) and dispersion  $\rho > v$ . In other words, the optic axial angle changes rapidly with the FeO percentage, being about  $90^\circ$  for FeO = 10 p. c. In the case of the chrysolites, the epidotes, the species triphylite and lithiophilite, and others, analogous relations have been made out.

**425. Optical Properties of Twin Crystals.** — The examination of sections of twin crystals of any other than the isometric system in polarized light serves to establish the compound character at once and also to show the relative orientation of the several parts. This is most distinct in the case of contact-twins, but is also well shown with penetration-twins, though here the parts are usually not separated by a sharp line.

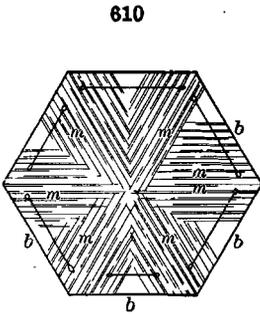
Thus the examination of a section parallel to  $b(010)$  of a twin crystal of gypsum, of the type of Fig. 608, makes it easy not only to establish the fact of the twinning but also to fix the relative positions of the ether-axes in the two parts. The measurement can in such cases be made between the extinction-directions in the two halves, instead of between one of these and some definite crystallographic line, as the vertical axis.

The polysynthetic twinning of certain species, as the triclinic feldspars, appears with great distinctness in polarized light. For example, in the case of a section of albite, parallel to the basal cleavage, the alternate bands extinguish together and assume the same tint when the quartz section is inserted. Hence the angle between these directions is easily measured, and this is obviously double the extinction-angle made with the edge  $b(010) \wedge c(001)$ . A basal section of microcline in the same way shows its compound twinning

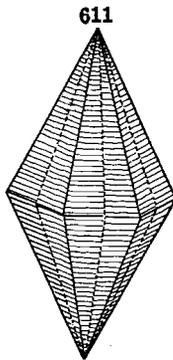
according to both the albite and pericline laws, the characteristic grating structure being clearly revealed in polarized light. Fig. 609 of a section of chondrodite (from Des Cloizeaux) shows how the compound structure is shown by optical examination; the position of the



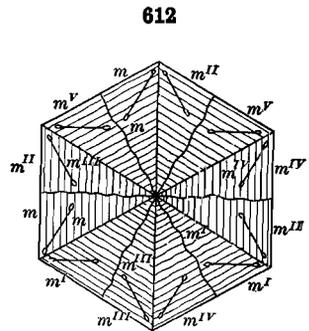
axial plane is indicated in the case of the successive polysynthetic lamella. The complex penetration-twins of right- and left-handed crystals of quartz (see the description of that species) also have their character strikingly revealed in polarized light.



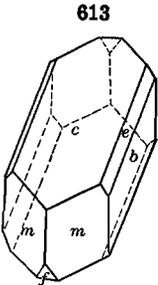
Witherite



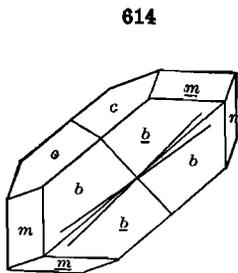
Bromlite (Des Cloizeaux)



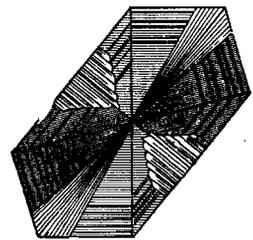
Still again, the true structure of complex multiple twins, exhibiting pseudo-symmetry in their external form, can only be fully made out in this way. This is illustrated by Fig. 610, a basal section of an apparent hexagonal pyramid of witherite. The analogous six-



613



614



615

Stilbite (Lasaulx)

sided pyramid of bromlite (Fig. 611) has a still more complex structure, as shown in Fig. 612. Fig. 613 shows a simple crystal of stilbite; Fig. 614 is the common type of twin-crystal, and Fig. 615 illustrates how the complex structure ( $\parallel b010$ ) is revealed in polarized

light. Other illustrations are given in Art. 429. It will be understood that the axial interference-figures of twin crystals, where the parts are superposed, often show many peculiarities; the Airy spirals of quartz (p. 270) will serve as an illustration.

**426.** A particularly interesting case, related to the subject discussed in the preceding article, is that of the special properties of superposed cleavage-sections of mica. If three or more of these, say of rectangular form, be superposed and so placed that the lines of the axial planes make equal angles of  $60^\circ$  ( $45^\circ$ , etc.) with each other the effect is that polarized light which has passed through the center suffers circular polarization, with a rotation to right or left according to the way in which the sections are built up. The interference-figure resembles that of a section of quartz cut normal to the axis.

If the sections are numerous and very thin the imitation of the phenomena of quartz is closer. These facts throw much light upon the ultimate molecular structure of a crystallized medium showing circular polarization. Further, it is easy from this to understand how it is possible to have in sections of certain crystals (*e.g.*, of clinocllore) portions which are biaxial and others that are uniaxial, the latter being due to an intimate twinning after this method of biaxial portions.

**427. Optical Properties of Crystalline Aggregates.** — The special optical phenomena of the different kinds of crystalline aggregates described on pp. 182, 183, and the extent to which their optical characters can be determined, depend upon the distinctness in the development of the individuals and their relative orientation. The case of ordinary granular, fibrous, or columnar aggregates needs no special discussion. Where, however, the doubly refracting grains are extremely small, the microscope may hardly serve to do more than to show the *aggregate polarization* present.

A case of special interest is that of spherulites, that is, aggregates spherical in form and radiated or concentric in structure; such aggregates occur with calcite, various chlorites, feldspars, etc. If they are formed of a doubly refracting crystalline mineral, or of an amorphous substance which has birefringent characters due to internal tension, they commonly exhibit a dark cross in the microscope between crossed nicols; further, this cross, as the section is revolved on the stage, though actually stationary, seems to rotate backward.

A distinct and more special case is that of spherical aggregates of a mineral optically uniaxial (or biaxial with a small angle). Sections of these (not central) in parallel polarized light show more or less distinctly the interference-figure of a uniaxial crystal. The objective must be focussed on a point a little removed from the section itself, say on the surface of the sphere of which it is a part. In such cases the + or - character of the double refraction can be determined as usual.

**428. Change of Optical Character Induced by Pressure.** — As the difference between the optical phenomena exhibited by an isometric crystal on the one hand and a uniaxial or biaxial crystal on the other is referred to a difference in molecular structure modifying the properties of the ether, it would be inferred that if an amorphous substance were subjected to conditions tending to develop an analogous difference in its molecular structure it would also show doubly refracting properties.

This is found to be the case. Glass which has been suddenly cooled from a state of fusion, and which is therefore characterized by strong internal tension, usually shows marked double refraction. Further, glass plates subjected to great mechanical pressure in one direction show in polarized light more or less distinct interference-curves. Gelatine sections, also, under pressure exhibit like phenomena. Even the strain in a glass block developed under the influence of unlike charges of electricity of great difference of potential on its opposite sides is sufficient to make it doubly refracting.

In an analogous manner the double refraction of a crystal may be changed by the application of mechanical force. Pressure exerted normal to the vertical axis of a section of a tetragonal or hexagonal crystal which has been cut  $\perp$  *c* axis, changes the uniaxial interference-figure into a biaxial, and with substances optically positive, the plane of the optic axes is parallel, and with negative substances normal, to the direction of pressure.

The quartz crystals in rocks, which have been subjected to great pressure, are often found to be in an abnormal state of tension, showing an undulatory extinction in polarized light.

**429. Optical Anomalies.** — Since the early investigations of Brewster, Herschel, and others (1815 *et seq.*) it has been recognized that many crystals exhibit optical phenomena which are not in harmony with the apparent symmetry of their external form. Crystals of many isometric species, as analcite, alum, boracite, garnet, etc., often show more or less pronounced double refraction, and sometimes they are distinctly uniaxial or biaxial. A section examined in parallel polarized light may show more or less sharply defined doubly refracting areas, or parallel bands or lamellæ with varying extinction. Occasionally, as noted by Klein in the case of garnet, while most crystals are normally isotropic, others show optical characters which seem to be determined by the external bounding faces and edges; thus, a dodecahedron may appear to be made up of twelve rhombic pyramids (biaxial) whose apices are at the center; a hexoctahedron similarly may seem to be made up of forty-eight triangular pyramids, etc.

Similarly, crystals of many common tetragonal or hexagonal species, as vesuvianite, zircon, beryl, apatite, corundum, chabazite, etc., give interference-figures resembling those of biaxial crystals. Also, analogous contradictions between form and optical characters are noted with crystals of orthorhombic and monoclinic species, *e.g.*, topaz, natrolite, orthoclase, etc. All cases such as those mentioned are embraced under the common term of *optical anomalies*.

This subject has been minutely studied by many investigators in recent years and important additions have been made to it both on the practical and the theoretical side. The result is that, though doubtful cases still remain, many of the typical ones have found a satisfactory explanation. No single theory, however, can be universally applied.

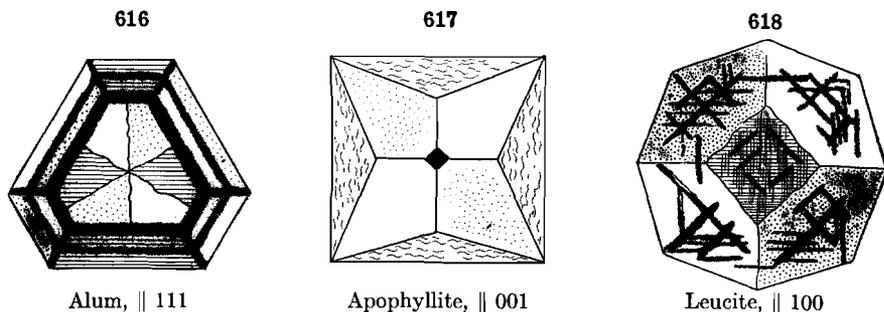
The chief question involved has been whether the anomalies are to be considered as secondary and non-essential, or whether they belong to the inherent molecular structure of the crystals in question. On the one hand, it has been urged that internal tension suffices (Art. 428) to call out double refraction in an isotropic substance or to give a uniaxial crystal the typical optical structure of a biaxial crystal. On the other hand, it is equally clear that twinning often produces pseudo-symmetry in external form, and at the same time conceals or changes the optical characters. From the simplest case, as that of aragonite, we pass to more complex cases, as witherite (Fig. 610), bromlite (Figs. 611, 612), phillipsite (Figs. 400, 452-454), which last is sometimes pseudo-isometric in form though optical study shows the monoclinic character of the individuals.\* Reasoning from the analogy of these last cases, Mallard was led (1876) to the theory that the optical anomalies could in most cases be explained by the assumption of a similar but still more intimate grouping of molecules which themselves without this would unite to form crystals of a lower grade of symmetry than that which their complex twinned crystals actually simulate.

In regard to the two points of view mentioned, it seems probable that internal tension (due to pressure, sudden cooling, or rapidity of growth, etc.) can be safely appealed to to explain the anomalous optical character of many species, as diamond, halite, beryl, quartz, etc. Again, it has been fully proved that the later growth of isomorphous layers of varying composition may

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\* Crystals showing pseudo-symmetry of highly complex type are called *mimetic* crystals by Tschermak.

produce optical anomalies, probably here also to be referred to tension. Alum is a striking example. The peculiarities of this species were early investigated by Biot and made by him the basis of his theory of "lamellar polarization," but the present explanation is doubtless the true one. Fig. 616 (from Brauns) shows the appearance in polarized light of a section  $\parallel o(111)$  from a crystal in which the successive layers have different composition. Further, according to Brauns, the optical peculiarities of many other species may be referred to this same cause. He includes here, particularly, those cases (as with some garnets) in which the optical characters seem to depend upon the external form, as noted above. Here belongs also apophyllite, a section of which (from Golden, Col., by Klein) is shown in Fig. 617. The section has been cut  $\parallel c(001)$



through the center of the crystal and is represented as it appears in parallel polarized light.

Another quite distinct but most important class is that including species such as boracite and leucite, which are *dimorphous*; that is, those species which at a certain elevation of temperature ( $300^\circ$  for boracite and  $500^\circ$  to  $600^\circ$  for leucite) become strictly isotropic. Under ordinary conditions, these species are anisotropic, but the fact stated makes it probable that originally their crystalline form and optical characters were in harmony. The relations for leucite deserve to be more minutely stated.

Leucite usually shows very feeble double refraction:  $\omega = 1.508$ ,  $\epsilon = 1.509$ . This anomalous double refraction, early noted (Brewster, Biot), was variously explained. In 1873, Rath, on the basis of careful measurements, referred the seemingly isometric crystals to the tetragonal system, the trapezohedral face 112 being taken as 111 and 211, 121 as 421, 241, respectively; also 101, 011 as 201, 021. Later Weisbach (1880), on the same ground, made them orthorhombic; Mallard, however, referred them (1876), chiefly on optical grounds, to the monoclinic system, and Fouqué and Lévy (1879) to the triclinic. The true symmetry, corresponding to the molecular structure which they possess or tend to possess at ordinary temperatures, is in doubt, but it has been shown (Klein, Penfield) that at  $500^\circ$  to  $600^\circ$  sections become isotropic; and further (Rosenbusch) that the twinning striations disappear on heating, to reappear again in new position on cooling. Sections ordinarily show twinning-lamellæ  $\parallel d(110)$ ; in some cases a bisectrix (+) is normal to what corresponds to a cubic face, the axial angle being very small. The structure corresponds in general (Klein) to the interpenetration of three crystals, in twinning position  $\parallel d$ , which may be equally or unequally developed; or there may be one fundamental individual with inclosed twinning-lamellæ. Fig. 618 shows a section of a crystal ( $\parallel a, 100$ ) which is apparently made up by the twinning of three individuals.

Still again, in a limited number of cases, it can be shown that the intergrowth of lamellæ having slightly different crystallographic orientation is the cause of the optical peculiarities. Prehnite is a conspicuous example of this class.

After all the various possible explanations have been applied there still remain, however, many species about which no certain conclusion can be reached. To many of these species the theory of Mallard may probably be applicable. Indeed it may be added that much difference of opinion still exists as to the cause of the "optical anomalies" in a considerable number of minerals.

## LITERATURE

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## IV. CHARACTERS DEPENDING UPON HEAT

**430.** The more important of the special properties of a mineral species with respect to heat include the following: Fusibility; conductivity and expansion,

\* A complete bibliography is given in the memoir by Brauns (1891), see above.