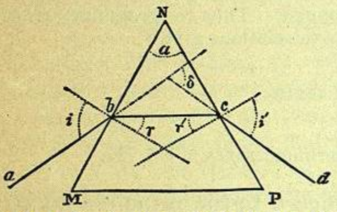
appearance also, under like conditions, of the surface of a transparent solid—for example, of a glass prism or a cut gem. The value of r thus found is called the *critical angle;* the smaller this angle the greater the apparent *brilliancy* of the given substance.

The relative refractive power of a given substance compared with that of the enclosing medium (*e.g.*, Canada balsam with $n_y = 1{\cdot}539$) determines on the principle of total reflection whether the surface appears rough with dark cracks ("high relief") as in garnet and zircon, or smooth and even ("low relief") as in quartz.

304. Determination of the Refractive Index.—By means of a prism, as MNP in Fig. 502, it is possible to determine the value of n, or refractive index of a given substance. The angle of the prism MNP, a, is, in each case, measured in the same manner as the angle between two faces of a crystal, and then the *minimum* amount of deviation (δ) of a *monochromatic* ray of light, *e.g.*, yellow sodium light, passing from a slit through the prism is also determined. The amount of deviation of a ray in passing through the prism varies with its position; but when the prism is so placed that the ray makes equal angles with the sides of the prism, that is, with the normals ($i = i'$, Fig. 502), when entering and emerging, this deviation has a *fixed minimum* value.

502.



If δ = the minimum deviation of the ray, and a = the angle of the prism, then

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

The application of this method is given in a later article. Several other methods are also explained—for example, one depending upon total reflection.

305. 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 the waves of different length, that is, the different colors of which ordinary white light is composed, being greater for blue than for red. In consequence of this fact, if ordinary light be passed through a prism, as in Fig. 502, 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).

306. Spectroscope.—The instrument most simply used for the analysis of the light by dispersion is familiar to all as the *spectroscope.** In it the light

from the given source, received through a narrow slit in the end of one tube, is made to fall as a plane-wave (that is, as a "pencil of parallel rays") upon one surface of a prism at the center, and the spectrum produced is viewed through a suitable telescope at the end of a second tube.

If the light from an incandescent solid—which is "white hot" (Art. **294**)—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.

307. Absorption.—Of the light incident upon the surface of a new medium, not only is part reflected (Art. **296**) and part transmitted and refracted (Art. **297**), 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.

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.

308. 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. **312**, **313**) 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,

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* A. de Gramont has shown that the direct spectroscopic examination of many mineral species (galena, pyrite) serves as a method of qualitative analysis and gives interesting results. Bull. Soc. Min., **18**, 171–373, 1895.

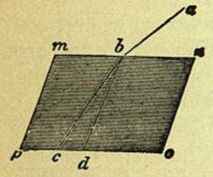
the phenomena are the same, and for the same causes, except that the bands are successive colored spectra.

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.

309. Double Refraction.—In the discussion of Art. **297**, 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. 503) 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 and also in Art. **300** 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.*

503.



310. When the incident light is perpendicular to the surface of the doubly-refracting substance, there is, in the more commonly occurring cases, no change of direction in the transmission; but even then it is usually still true that the incident ray is divided into two rays, which, though they may travel in the same path, yet have different velocities, so that one falls behind the other. Further, as later explained, each is in general plane-polarized. For each of these rays, it is true that for waves of the *same length* the rate of transverse vibration, and hence the velocity of the ray itself, is inversely proportional to the respective refractive index.

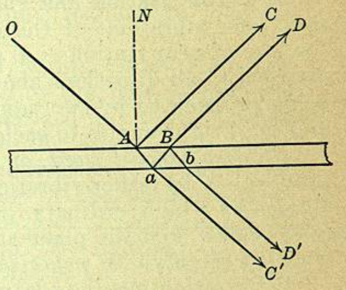
311. Interference of Waves in General.—The subject of the interference of light-waves, alluded to in Art. **308**, requires detailed discussion. It is one of great importance, since it serves to explain many common and beautiful phenomena in the optical study of crystals, for example, the axial interference figures shown on the plate forming the frontispiece.

Referring again to the water-waves spoken of in Art. **287**, 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 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. **289**).

312. 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). If, however, the waves differ in phase by half a wave-length, or an odd multiple of this, they *interfere* and extinguish each other. 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 these cases monochromatic light-waves were assumed (that is, those of like length). If ordinary white light is used, the waves in the case of interference will overlap, and their interference will be indicated by the appearance of the colors of the spectrum.

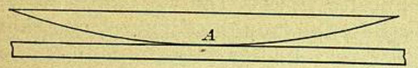
313. Illustrations of Interference.—A simple illustration is afforded by the bright colors of very thin films or plates, as a film of oil on water, a soap-bubble, and like cases. To understand these, it is only necessary to remember that the incident light-waves are reflected in part from the upper and in part from the lower surface of the film or plate. Hence if the thickness is very small, these two reflected wave-systems, when they come together (represented in Fig. 504 by the two rays *AC*, *BD*) will differ from one another in phase, and interfering give rise (in ordinary light) to the colored phenomena spoken of. 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 which 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) is that determined by the retardation 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.

504.



A plano-convex lens of long curvature, resting on a plane glass surface (Fig. 505), 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 latter 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 their smaller wave-length. In each of the cases described the ring is properly the intersection on the plane surface of the cone of rays of like retardation.

505.



In ordinary white light there can be no dark rings because of the difference of length of the component waves; on the contrary, the overlapping of these waves produces a series of *colored rings*, each showing the successive colors of the spectrum. The series of colors are distinguished as of the first, second, third, etc., order; for a given color, as red, may be repeated a number of times as the waves overlap. After a certain number of waves have overlapped in this way, white light ("of a higher grade") results.

Similarly in the case of the thin plate in white light, a certain thickness and consequent retardation produces a superposition of the waves which yields, for example, a shade of red; a greater thickness (and retardation) a red of the second order, etc. If the plate is not very thin, simple white is reflected from it.

Another most satisfactory illustration of the interference of light-waves is given by means of the diffraction gratings spoken of in Art. **308**, but the subject cannot be further discussed in this place.

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

314. Polarization and Polarized Light.—Ordinary light is propagated by transverse vibrations of the ether which take place alike in all planes about the line of propagation. A ray of ordinary light is, therefore, alike or symmetrical in all directions about this line; it may be most simply thought of as being propagated by two equal sets of transverse vibrations taken in any two planes at right angles to each other.

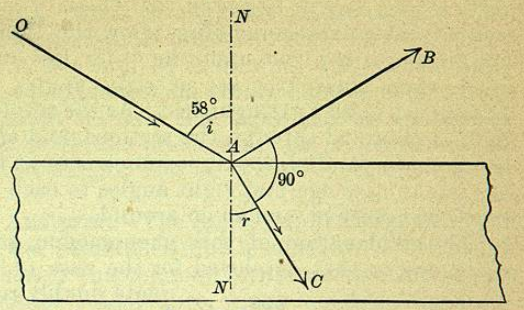
Plane-polarized light, on the other hand, as stated briefly in Art. **291**, is propagated by ether-vibrations which take place *in one plane only*. The change by which ordinary light is changed into a polarized light is called *polarization*, and the plane at right angles to the plane of transverse vibration is called the *plane of polarization.**

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

315. 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 a given angle of incidence, varying for each substance, but such that the reflected and refracted rays (AB and AC, Fig. 506) make an angle of 90° with each other, this polarization is a maximum. For this case it is hence true, if we represent this angle of polarization by i, that

$$\tan i = n.$$

506.

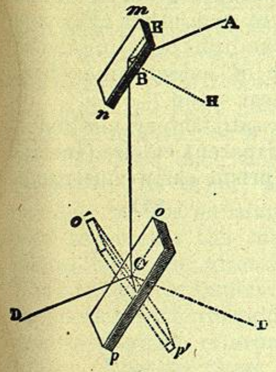


This law, established by Brewster, may be stated as follows:

The angle of polarization is that angle whose tangent is the index of refraction of the reflecting substance. For crown glass this angle is about 58° (see Fig. 506). 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.

If the polarized light-waves fall upon a second similar reflecting surface at the same angle, they will be reflected again unchanged, on the condition that the two planes of incidence (and hence the two planes of polarization) of the two mirrors coincide. If, however, these planes are at right angles to each other, the light polarized by the first mirror will be extinguished by the second. As the polarization is in no position absolutely complete, the light is not completely arrested, but only reduced to a minimum in the second position.

507.



This case is illustrated by Fig. 507. Here the incident ray AB is reflected by the first mirror mn in the direction BC and polarized in a plane normal to the plane of incidence – the angle ABH being equal to the angle of polarization. If now the second mirror occupy either of the positions op or $o'p'$, the planes of incidence (and of polarization) of both mirrors coincide and the light-ray, BC, is, therefore, reflected a second time in the direction of oD, or oD'. If, however, the second mirror be revolved about a vertical axis the reflected light becomes gradually weaker and is sensibly extinguished when the two planes of incidence are at right angles to each other.

316. Polarization by Double Refraction.—When light in passing through a crystalline medium is doubly refracted (Art. **309**) 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 that due to a single set of vibrations only is transmitted. This is accomplished by natural absorption in the case of tourmaline plates and by artificial means in the nicol prisms of calcite.

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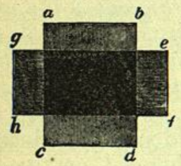
* This is in accordance with the assumption of Fresnel; with MacCullagh the vibration-plane and plane of polarization coincide. All ambiguity is avoided by speaking uniformly of the *vibration-plane* of the light.

317. Polarized Light by Absorption.—If from a crystal of tourmaline, which is suitably transparent, two sections be obtained, each cut parallel to the vertical axis, it will be found that these, when placed together with the direction of their axes coinciding, allow the light to pass through. If, however, one section is revolved upon the other, less and less of the light is transmitted, until, when their axes are at right angles (90°) to each other, the light is (almost perfectly) extinguished. As the revolution is continued, more and more light is obtained through the sections, and after a revolution of 180°, the axes being again parallel, the appearance is as at first. A further revolution (270°) brings the axes again at right angles to each other, when the light is a second time extinguished, and so on around.

The explanation of this phenomenon, so far as it can be given here, is analogous to that employed for the case of polarization by reflection. Each plate doubly refracts the light; but one of the two sets of waves is absorbed, and only that set whose vibrations are parallel to the vertical axis are transmitted. If now the two plates are placed in the same position, *abdc*, and *efhg* (Fig. 508), the light passes through both in succession. If, however, the one is turned upon the other, only that portion of the light can pass through which vibrates still in the direction *ac*. This portion is determined by the resolution of the existing vibrations in accordance with the principle of the parallelogram of forces. Consequently, when the sections stand at right angles to each other (Fig. 509) the amount of transmitted light is nearly zero, that is, the light is extinguished. Instead of tourmaline, an artificial salt, the sulphate of iodoquinine (herapathite) is sometimes employed, but it has little practical value.

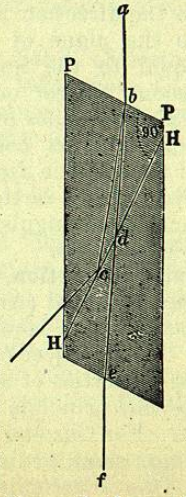
508.

509.

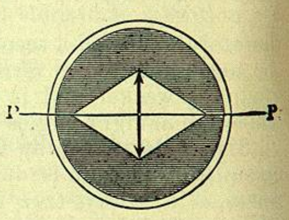


318. Polarized Light by Nicol Prisms.—The most satisfactory method of obtaining polarized light is by means of a prism of transparent calcite (Iceland spar). Fig. 510 shows the principle involved in the prism early constructed by Nicol, which transmits one only of the two refracted rays, that represented by the line *bde* (the extraordinary ray, as later defined). The other ray, *bc*, suffers total reflection at the surface where the two sections are united together by Canada balsam and is then absorbed by the black surface of the sides. Here the vertical faces are natural cleavage-faces; the face *PP* is ground on so as to make an angle of 68° with the obtuse vertical angle; the prism so formed is cut diagonally across (*HH*), and then the parts cemented together. This form of prism, as well as others somewhat different in form but accomplishing the same end with the use of less material, is ordinarily called a Nicol prism, or briefly a *nicol*. The section of the ordinary nicol of Fig. 510 is lozenge-shaped (Fig. 511); the plane of polarization, *PP*, passes through the acute angles of the cross-section, and the vibration-plane, here as usual represented by a double-headed arrow, passes through the obtuse edges. The other prisms alluded to may have a rectangular cross-section. The vibration-plane can be readily determined in any case by examining with it the light reflected from some suitable surface (*e.g.*, of a wood table). Twice in a revolution of the prism through 360° about its axis this light will be weakened; when this is true, the vibration-plane of the prism must be perpendicular to that of the partially polarized reflected light, that is, it must be *vertical*, since the latter is taken as horizontal.

510.



511.

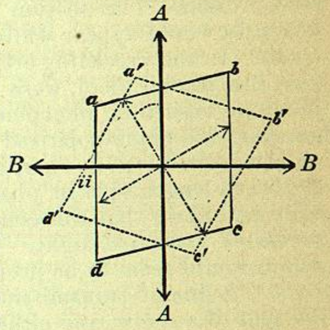


319. Polariscope. Polarizer. Analyzer.—The combination of two nicols, or other polarizing contrivances, for the examination of a substance in polarized light is called, in general, a *polariscope;* the common forms are described later. In any polariscope the prism, or other contrivance, which polarizes the light given from the outside source is called the *polarizer;* the other is the *analyzer.* If the prisms have their vibration-planes at right angles to each other, they are said to be *crossed;* the incident light polarized by the polarizer is then extinguished by the analyzer; briefly, it is said to suffer *extinction.*

320. Interference of Plane-polarized Waves. Interference-colors.—The simplest case of the interference (Art. **312**) of polarized light to consider is that where the two light-waves, or, more simple expressed, two rays, are polarized in the *same plane.* They may then interfere to extinguish each other, or they may give rise to beautiful color-effects.

Suppose, for example, that in a polarization-microscope (Art. **328**) parallel light passes upwards through the lower nicol, whose vibration-plane is shown in the cross-section of Fig. 512 by the arrow *AA*; this light is polarized in a single plane. Now let this polarized light pass through a thin cleavage-plate of selenite; it will in general be separated into two rays, each polarized in planes at right angles to the other, having a definite position peculiar to this substance. Thus, in Fig. 512, if *abcd* represents the selenite plate, its vibration-planes have the directions of the dotted arrows. The two rays corresponding to them travel through the section with unequal velocity, and on emerging one is slightly retarded as compared with the other. Now let these light-rays pass through a second nicol, with its vibration-plane at right angles to that of the first nicol, that is, in the direction of the arrow *BB*. Then each of the two sets of vibrations (represented by the dotted arrows) will have a component in the direction of *BB*, and these will emerge now polarized in the same plane, and hence capable of interfering, for light-rays can only thus completely interfere when their vibrations are in a common plane. Further, an amount of light corresponding to the other components (in the direction *AA*) will be extinguished. One of these emergent rays is, as stated, slightly retarded as compared with the other. The amount of this retardation obviously varies with the strength of the double refraction (in this case $\gamma - \alpha$), and also with the thickness of the section taken. The interference-color of the section, supposing ordinary light to be used, depends upon these two conditions, and may be calculated for a given substance. Thus a plate of selenite of a thickness of 0·055 mm. will give a red (of the *first order*), and if thinner,

512.



a yellow or gray. As the thickness increases, the colors (now of the *second order*) pass through successive shades of blue, green, yellow, orange, and if the plate is of sufficient thickness a second red and so on (see, further, Arts. **359** and **382**). A mineral of very strong double refraction, as calcite, shows only the white of the higher order unless extremely thin.

If the section had happened to have the position of $a'b'c'd'$ (Fig. 512), its vibration-planes would have coincided with those of the two nicols, and the light, after passing through the first nicol and the section, would have been propagated by vibrations in the direction AA only, and hence have been completely extinguished by the second nicol. The plate would then have appeared dark.

The successive interference-colors* of the *first order* pass from an iron-gray through bluish-gray to white, yellow, and red; then follow indigo, blue, green, yellow, orange, and red of the *second order;* then the similar but paler series of colors of the *third order*, and finally the very pale shades of green and red of the *fourth order*. Beyond this the colors are not very distinct; white of a higher order finally results from the interference.

An excellent colored plate showing these colored bands is given by Lévy and Lacroix (Les Minéraux des Roches, 1888). It is so arranged as to give the thickness of the section of a given mineral (all important species present in rocks being included) which will yield any one of the different shades of color mentioned. The use to which such a plate may be put in the practical determination of the birefringence of a given mineral will be referred to later.

321. Complementary Colors in Polarized Light.—If in the examination of the selenite plate, as just described (Art. **320**), one of the nicols had been rotated 90°, or, in other words, if the vibration-planes of the two nicols had been made parallel, then it is obvious that interference would also have taken place between the emerging rays, but the color resulting in each case would have been exactly the *complementary* tint to that obtained at first when the nicols were crossed. The section in the position $a'b'c'd'$ between parallel nicols obviously would appear white.

322. 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 easily be shown that the composition of these two systems results in a ray of *circularly polarized* light. Briefly expressed, this is a ray which 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° 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 $\frac{\lambda}{2}$ or λ), the emergent light is elliptically polarized.

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* See further the table given in the following article; also the explanation of the "ultra-blue" on p. 428.

The following table from Klein* gives the relation between the retardation from $\frac{1}{8}\lambda$ to 2λ (λ = wave-length) for a section of a doubly refractive substance, the interference-color it yields, and the state of the transmitted light as regards polarization. The section is supposed to be observed in parallel sodium light with crossed nicols; further, the vibration-direction corresponding to the greater refractive index in the section runs from left in front to right behind.

Retardation for Na light.	*Interference-color* Nicols (+), white light.		*Kind of Polarization.*
$\frac{1}{8}\lambda$	Lavender-gray	1ST ORDER	Elliptic, right-handed.
$\frac{1}{4}\lambda$	Grayish-blue	"	Circular, "
$\frac{3}{8}\lambda$	Clearer-gray	"	Elliptic, "
$\frac{1}{2}\lambda$	Pale straw-yellow	"	*Plane-polarized.*
$\frac{5}{8}\lambda$	Bright yellow	"	Elliptic, left-handed.
$\frac{3}{4}\lambda$	Brownish-yellow	"	Circular, "
$\frac{7}{8}\lambda$	Orange	"	Elliptic, "
λ	Red	"	*Plane-polarized.*
$\frac{9}{8}\lambda$	Indigo	2D ORDER	Elliptic, right-handed.
$\frac{5}{4}\lambda$	Azure-blue	"	Circular, "
$\frac{11}{8}\lambda$	Green	"	Elliptic, "
$\frac{3}{2}\lambda$	Brighter green	"	*Plane-polarized.*
$\frac{13}{8}\lambda$	Yellow	"	Elliptic, left-handed.
$\frac{14}{8}\lambda$	Orange	"	Circular, "
$\frac{15}{8}\lambda$	Reddish-orange	"	Elliptic, "
2λ	Dark violet-red	"	*Plane-polarized.*

323. Crystals Giving Circular 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 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 groups of lower symmetry than the normal group which show a plagihedral development of the faces;† or, more simply, those in which the corresponding right and left (or + and −) typical forms are enantiomorphous (pp. 50, 82), as noted in the chapter on crystallography. In mineralogy, this subject is most important with the common species quartz, of the rhombohedral-trapezohedral group, and a further discussion of it is postponed to a later page (Art. **366**).

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* Ber. Ak. Berlin, 221, 1893.

† Of the thirty-two possible groups among crystals, the following eleven may be characterized by circular polarization: Group 4, p. 50; 5, p. 51; 11 and 12, p. 63; 17, p. 73; 22, p. 82; 23 and 24, p. 84; 27, p. 96; 29, p. 103; 32, p. 109.