

QUARTZ: A BULL'S EYE ON OPTICAL ACTIVITY



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Title: Quartz: a Bull's Eye on Optical Activity

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Edition: First edition

Publisher: Mineralogical Society of America, Chantilly, Virginia, USA

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ISBN: 978-0-939950-00-3

**Photographer
& Designer:** Elise A. Skalwold

Front cover: Natural quartz crystal 60 x 65 x 40 mm; Hot Springs, Arkansas;
ex. Dr. R.W.M. Woodside collection.

Back cover: Lab-grown quartz cluster, 140 mm x 90 mm
(hydrothermally grown by Mila and Vladimir A. Klipov, R&D XTALS, Inc.).

Below: Natural quartz crystals and basal sections.



On-going collaboration with Cornell's Professor Emeritus William A. Bassett is truly priceless to me for this and other projects in the wings, as well as for those over the past eight years of work and research together. Bill shares my enthusiasm for exploring the fascinating aspects of the classical science of mineralogy, and as my co-author he sets the highest bar for accuracy. All students should be so lucky to have such a mentor.

*Elise A. Skalvold, 2015
Ithaca, New York*

QUARTZ: A **BULL'S EYE** ON **OPTICAL ACTIVITY**

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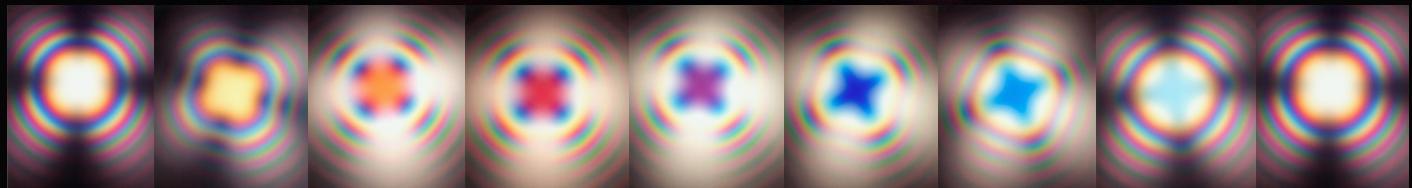


Figure 1. The “bull’s eye” uniaxial optic figure characteristic of quartz is indicative of its optical activity. This is the view seen looking directly along the optic axis of the crystal when viewed between two *crossed* polarizing filters in transmitted white light - that is, looking towards the light source. The N-S, E-W dark areas are the remnants of isogyres which in uniaxial minerals normally form a black cross in the center, but which in slices thicker than 1 mm are extinguished by quartz’s strong optical activity and low birefringence, thus forming the bull’s eye appearance. The outer rings of color are isochromes and follow those of Newton’s Rings. The central colors recombine with increased thickness and ultimately leave only a red changing to green sequence in the center. Rotating the filter farthest from the light source in a clockwise direction for 180 degrees cycles the bull’s eye through a series of colors and shapes *that depend on thickness*. For this 3.0 mm basal slice, the left to right sequence of changing colors indicates that it is likely an optically left-handed quartz; confirmed with observation using a quarter-wave plate as seen in Figure 5 or by direct measurement with monochromatic light as seen in Figure 11.

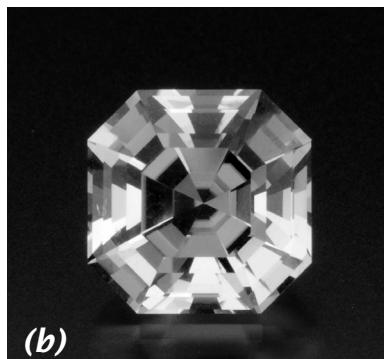
Prelude

It might be overstating a bit to say that if one could understand all there is to know about quartz, then everything else in the universe would make sense. Without doubt, this mineral has profoundly impacted many sciences and technologies which we rely upon today. At the very least, quartz provides one with a host of mental gymnastics and a seemingly endless variety of puzzles to ponder. Not least among its fascinating properties is that of *optical activity*, its manifestation of

which results in the special optical figure affectionately known as the “bull’s eye.” In the authors’ article on causation of blue color in minerals, mention is made of the quartz monochromator, an obscure instrument which makes use of optical activity in a very elegant way (Skalwold and Bassett 2016). In hopes of giving readers insights and appreciation for this ingenious device and for quartz itself, the following is an exploration into the nature of the chromatic phenomenon which plays out within this proverbial black box.

Figure 2a: The presence and orientation of several different faces and surface features may be used to determine the handedness of a quartz crystal (note: these are not always present in all crystals or crystal fragments). For example, the presence of the left-leaning trigonal pyramid *s* face under the positive *r* and negative *z* rhombohedral faces on the large quartz crystal at right makes it easily identifiable as having left-handed ***morphology*** (had the *s* face been located under the opposite lower corner of the *r* face and leaning to the right, it would have been designated a ***morphologically*** right-handed crystal). Given this external appearance, this crystal will also be ***optically*** left-handed, but internally it will be ***structurally*** right-handed; a characteristic only discernible with advanced laboratory instrumentation. Hot Springs, Arkansas; ex. R.W.M. Woodside collection, 60 x 65 x 40 mm.

Figure 2b: In the absence of crystal faces, such as a fragment, a basal slice or a fashioned gemstone such as the one at left, handedness can be determined by using transmitted light to observe the bull's eye optic figure between crossed polarizing filters as seen in Figure



1. This Asscher cut gem is oriented with the optic axis exactly perpendicular to the table facet; that is, in this image it is coming directly out of the page at the viewer. The nature of its optical activity indicates that it is ***optically*** right-handed. Mt. Ida, Arkansas, collected and faceted by Peter Torracca; 1.62 carats, 7.10 x 7.10 x 5.61 mm.



Note: Both specimens are from the same general locality, but are of opposite handedness. It is believed that in nature, left and right-handed quartz occurs in equal numbers. By convention most synthetic quartz is optically right-handed, though some companies specialize in left-handed crystals. Either way, the handedness of the synthetic crystal is set by that of the seed crystal used to grow it.

Open any textbook on optical mineralogy and one will find illustrations of the optic figure produced by all uniaxial minerals including quartz, as well as variations caused by such factors as angle of viewing, twinning and structural distortions. Less frequently, one will find an illustration of the curious bull's eye optic figure seen in relatively thick slices of quartz, so named for its appearance reminiscent of a target (Fig. 1). In mineralogy this is seldom encountered as study with the petrographic microscope involves thin sections usually no more than 30 microns (0.03 millimeters); well under the one millimeter thickness above which the normally seen crossed dark isogyres begin to fade in the center due to quartz's strong optical activity and low birefringence, thus forming the bull's eye appearance. This fascinating manifestation of optical activity may be overlooked entirely, though the concept may be a notion stored away in the cranial filing cabinet along with other required, but rarely used academic trivia learned in the pursuit of one's chosen geologic field. Gemologists and lapidaries are usually quite familiar with the bull's eye for it is used to instantly identify an

unknown specimen as being quartz and for orienting the c-axis/optic axis of pieces of rough in preparation for fashioning; though its underlying cause is very rarely understood in any depth as it is not needed for those tasks. In a few cases, the varying color of its center has even been cause for alarm, lest it indicate possible tampering with its natural condition or even that it indicates a synthetic imposter.

A word to the wise

At different periods of time throughout the history of optical mineralogy definitions of terms and conventions have not always been consistent, either because of changing nomenclature as understanding evolved or because of the personal preference of the author. This can be seen across different types of publications old and new and across different specialties – a situation which can lead to great confusion, frustration and even inadvertent misuse of terms. The favored texts of the current authors are Wahlstrom (1969), Frondel (1962), and Tutton (1924); the conventions used in the present article are described below.



When discussing handedness and optical activity, a very common source of confusion is that of point of view (POV). Quartz occurs as either left or right-handed crystals based on several criteria, but the convention for the type of handedness has varied over the last nearly two centuries. Unless otherwise stated, the current authors' POV is that of looking along the crystal's optic axis *toward* the source of light (note: the optic axis of quartz is parallel to its crystallographic c-axis, but is not confined to just that symmetry axis, only to the same direction of it). Here is where it gets tricky: quartz is *morphologically* and *optically* of the same handedness, but its *structural* handedness is opposite that of the former two (Fig. 2), a fact which was not known until modern advanced instrumentation was available with which to explore atomic structure (Frondel 1962, Wahlstrom 1969).

When crossed polars (polarizing filters or nicol prisms) are used, it is meant that polarization directions or vibration directions of each are at 90 degrees to each other. The start of most observations is when they are north-south and east-west (N-S, E-W), at which orientations the field of view (without a sample) is darkest.

Figure 3: There are various ways of viewing specimens between polarizing filters. One is to use a polariscope, such the model at left. A fixed filter termed the *polarizer* is at the bottom and a rotatable filter termed the *analyzer* is at the top. Transmitted light is provided by a bulb in the base (or by an external light for other models). A similar setup may be used in microscopes either with provided filters or by using a portable polariscope resting on the stage. The sphere on the end of the glass rod is strain-free and is used to resolve the optic figure; a 10x loupe works just as well. A number of test specimens are shown, including 3 mm and 14.75 mm basal sections and a 10 mm sphere (all on the stage); faceted purple, yellow and colorless quartz specimens – the latter two optical-quality quartz were optically oriented by the author (EAS) and custom cut by Mark Oros. The two milky white cabochons from Sri Lanka feature multi-star networks; using the bull's eye to orient them makes it easy to study their fascinating intricate networks, especially in spherical versions.

In a polariscope such as the one shown in Figure 3, the upper filter farthest from the light source is termed the “analyzer” and the lower one is termed the “polarizer.” Both may be rotated, though in many instruments the polarizer is stationary and/or should remain so.

In many publications the term “circular polarization” is used in defining optical activity. This can be misleading. For example: light emerging from a filter designed to produce *circularly* polarized light consisting of a polarizing filter and $\frac{1}{4}$ -wave plate continues to be circularly polarized *after* leaving the plate, whereas the light leaving a quartz crystal having traveled along the optic axis is *plane* polarized after leaving the crystal. And so the two principles are fundamentally different. The current authors prefer not to use the term “circular” when envisioning the experience of light as it travels along the optic axis of quartz, but rather feel “rotatory” is a far better descriptor for it.

Going down the rabbit hole

The simplest way to observe the bull's eye optic figure is to obtain plane polarizing filters such as from a pair of sunglasses, a sun visor from the auto parts store or dedicated filters from an optical supply catalog (do not use circular polarizing filters designed for digital cameras). While holding the filter very close to the eye with the specimen close to the other side of the filter, use polarized light such as provided by reflection off of a non-metallic surface or emanating from a computer or smart phone screen (avoid using a screen which has a birefringent screen protector, such as is sometimes applied onto smart phones). Determine the crossed orientation by rotating one of the filters until the view is at the darkest point. Alternatively, hold the specimen further away towards the light and use a 10x loupe between the specimen and filter to resolve the bull's eye.

By using two filters and a fiberoptic light source, the optic figure may also be projected onto a white surface thus making it easier for several people to observe at the same time (Figs. 4 and 6).

It is very convenient to have a dedicated polariscope, either a stand-alone model as seen in Figure 3 or as a portable type for use with a flashlight or under a microscope (some microscopes have movable polarizing filters built into them). Of course, one can also build a polariscope using the same design premise and scavenged materials. A polariscope is very handy for examining a variety of quartz specimens (as well as other minerals), including various colors, basal sections, spheres and large fragments. Of particular interest are quartz spheres and cabochons which manifest a network of six-ray and four ray stars over their entire surface. Being able to quickly orient both ends of the optic axis by their bull's eye figures helps one decipher the crystallographic influences dictating the networks—a favorite exercise of this author (EAS). Even pristine spheres free of any inclusions or asterism are fascinating to explore in a polariscope (for a guided optical tour of a clean quartz sphere, see page 432 of Dyar and Gunter 2008).

Starting with polars crossed, turning the analyzer clockwise causes the central color to change sequentially (Fig. 1). A.E. H. Tutton gives the following rule, quoted with all his punctuation and spelling preserved:

“...for a right-handed crystal rotation of the analyser to the right causes the colours to appear in the order of their refrangibility, namely, the least refrangible red first, then orange, yellow, green, blue and violet in their order; while for a left-handed crystal the converse is true when the direction of rotation of the analyser is the same, that is, to the right, clockwise; obviously also the colours appear in the opposite order when the rotation of the analyser is to the left.” (page 190, Tutton 1924)

Remember that increasing thickness changes the colors seen, but not their sequential ordering (Fig. 6b); the colors will follow a similar sequence as is seen

Figure 4: With the 3 mm basal slice of Figure 1 sandwiched between crossed polarizing filters, a fiberoptic light is used here to project the bull's eye optic figure onto a white surface.



in retardation versus thickness charts found in most optical mineralogy texts (see chart in Dyar and Gunter 2008). Two basal sections stacked together may be used to demonstrate this, *but* because the central color is complicated in its origins and depends on thickness, *color sequence alone should not be used* to determine handedness. Confirmation of handedness can be made by observing the figure while employing a quarter wave plate

(or a *very* thin cleavage wafer of muscovite mica) between the crystal and analyzer which will produce a left or right-handed spiral in the bull's eye accordingly (Fig. 5). Also, two basal sections of opposite handedness stacked together without a quarter-wave plate produce a combined “Airy’s spiral,” as seen in quartz twinned on the Brazil law and commonly found in amethyst.

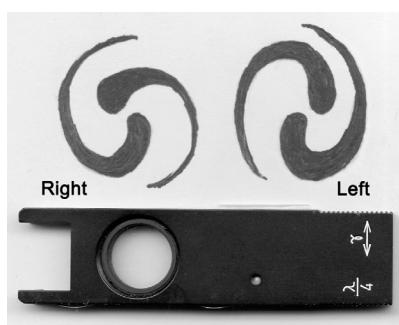


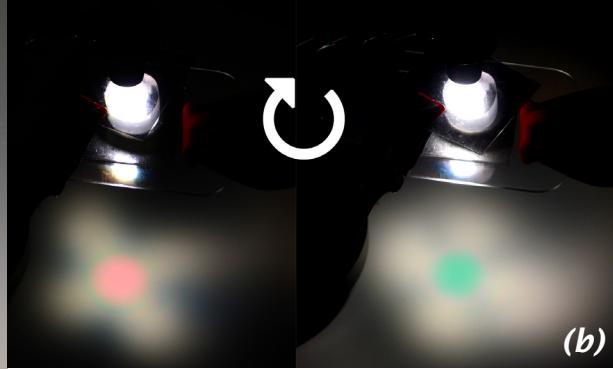
Figure 5: Above: a quarter-wave plate with right or left-handed spiral as seen through its round window when placed between crystal and analyzer. Below: Airy's spiral in the 3 mm left-handed basal section of figure 1.



Having been so enamored with these observations since first encountered, with the help of her coauthor, this author (EAS) long ago condensed her understanding of optical activity in quartz into the following summary; printed out and inserted into nearly every publication mentioning quartz in her library; it has been the keystone of her fascination with this mineral: *The bull's eye optic figure results from the quartz's optical activity: as light passes through the crystal, its plane of vibration is rotated. The amount of rotation (**rotatory power**) is measured in degrees per millimeter and is dif-*



(a)



(b)

Figure 6a: A simple setup for observation of optical activity in quartz; essentially an upside down polariscope. Polarizing filters may be purchased from a supply catalog or removed from a pair of old sunglasses. **Figure 6b:** Thickness affects the colors seen in the center. In contrast to Fig. 1, a 14.75 mm thick basal slice produces a red > yellow > green bull's eye color sequence when the filter is turned clockwise, indicating that it is likely an optically right-handed crystal; confirmed with observation using a quarter-wave plate or a very thin cleavage wafer of muscovite mica.

ferent for different wavelengths (**rotatory dispersion**); that is, the shorter wavelengths are rotated more, longer wavelengths are rotated less (see Table 1). There is strong rotation of the plane of vibration of light transmitted parallel to the optic axis; the colored center of the eye is where this effect overcomes the quartz's low birefringence, obscuring the isogyres which reappear further out from the center. The color seen in the center of the bull's eye depends on the thickness of the quartz and at what point in the rotation that the light emerges from the crystal; **it is not an interference color**. The colors appear similar to interference colors as both are a mixture of spectral colors, but for different reasons (Tutton 1924; Wahlstrom 1969). This summary is expanded upon in the following section—put your seatbelts on!

TABLE 1. ROTATION OF PLANE OF POLARIZATION BY QUARTZ

λ in Å	Rotation in degrees	
	1 mm. thick	53 mm. thick
7600	12.67	671.51
6708	16.54	876.62
6563	17.32	917.96
5890	21.68	1,149.04
5461	25.70	1,362.10
5270	27.54	1,459.62
5086	29.72	1,575.16
4861	32.77	1,736.81
4340	42.60	2,257.80
4047	48.93	2,593.29
3934	52.15	2,763.95

APPROXIMATE LIMITS OF VISIBILITY		
λ in Å	Rotation in degrees	
	1 mm.	53 mm.
4000	49.0	2,597
7000	15.3	811
Difference in rotation between extremes	33.7	1,786

Table 1: Note: 7600 angstroms equals 760 nanometers (Hurlbut and Rosenfeld 1952, page 159; courtesy of the Mineralogical Society of America).

The mechanism of rotation, a form of dispersion

When plane polarized light enters a quartz crystal and travels parallel to its optic axis, the plane of polarization is rotated into a cork screw or more accurately a helix and continues to rotate until it arrives at the other side of the crystal. The amount of rotation depends on the frequency of the light; the higher the frequency, the greater the rotation (Table 1). This phenomenon is a form of dispersion which is more commonly manifested as the dependence of light velocity on the frequency of the light as it passes through a transparent material.

To understand dispersion, including rotation, the interaction between light and atoms can be thought of as taking place when the frequency of the light causes vibration of atoms in the mineral (Jenkins and White 1957). Because the nucleus of an atom is more massive than the electron cloud around the nucleus, it is the electron cloud that is set into vibration by the frequency of the light. The electron cloud acts as if it is bound to the nucleus by rubber bands. The electron cloud responds more strongly to the higher frequencies of light, i.e., it responds more vigorously to the higher (bluer) frequencies. The electron cloud then reemits light much as a radio antenna emits radio waves as the electrons in the antenna move up and down. The stronger the vibration of the electron cloud, the longer it takes for it to reemit light. The newly emitted light then joins the light that missed the atom and makes it appear to travel more slowly when actually it only delayed it for a tiny fraction of a second. When all the small delays are summed up, the effect is to make the

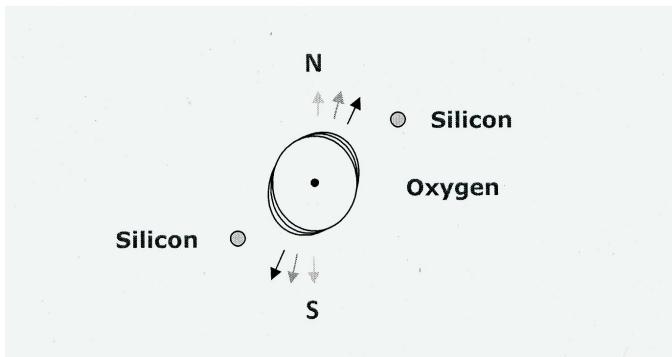


Figure 7: If light coming toward you along the c-axis of quartz is plane polarized N-S, the electron clouds of the oxygen atoms will be set vibrating N-S. If the quartz is right-handed and nearby silicon atoms are positioned as in the diagram, their attraction causes the vibration direction to rotate clockwise. If the silicon atoms are not positioned this way in the first layer, they will be in the other layers. This is because the c-axis is also a screw symmetry axis (diagram by author WAB).

light travel more slowly. It is the dependence of velocity on frequency that is responsible for the separation of colors when white light passes through a prism or is reflected through facets at an angle in a faceted stone with a high dispersion such as diamond.

In most transparent materials the electron clouds of atoms continue to vibrate in the same direction. But, if all the atoms are bound in distorted sites like the oxygen atoms in quartz, the vibration of the electron cloud is affected by the neighboring atoms (silicon in the case of quartz) which persuade the oxygen's electron cloud to begin to vibrate in a *new* direction before it reemits light (Fig. 7).

If this effect is in the same direction for most of the oxygen atoms in the crystal, summing up all the tiny changes in angle has the effect of rotating the polarization direction of the light, and the light has a new polarization direction when it emerges from the far side of the crystal. And just as in the more common dispersion, the higher the frequency, the stronger the effect. That is why light at the blue end of the spectrum is rotated more than light at the red end of the spectrum.

Quartz has two different ways of crystallizing depending on whether rows of atoms are stacked along the c-axis with a right-handed screw or a left-handed screw. This in turn determines whether the polarization direction rotates clockwise or counter-clockwise as light travels toward you parallel to the c-axis. If the stacking of the rows of atoms has a right handed (clockwise) screw symmetry axis, the rows of atoms have a coun-

ter-clockwise stacking as they come toward you, just as a nut on a right handed bolt will turn counter-clockwise as it comes toward you. And so, quartz with its right-handed symmetry element will cause polarized light to rotate counter-clockwise as it comes toward you.

It is rarely pointed out that the variation of light velocity as it passes through a transparent material does not violate Einstein's theory of relativity. Instead light can be thought of as being delayed at each atom but traveling between atoms at the velocity of light in a vacuum.

The quartz monochromator, an elegant use of the rotatory power of quartz

White light can be separated into an entire visible spectrum, and specific wavelengths of light may be isolated for use in a number of applications where a monochromatic light is needed; for example, in order to identify gems and minerals an instrument called a refractometer is calibrated on the basis of using yellow 589.3 nanometer (nm) sodium light. There are various methods to produce monochromatic light, such as monochromatic filters and diffraction gratings which utilize the phenomenon of *interference* to produce narrow band spectral color and prisms which *bend* light to separate different wavelengths (Skalwold and Bassett 2016).

In the mid-1900s, Dr. Cornelius S. Hurlbut, Jr. of Harvard University realized that the rotatory dispersion generated by quartz as described above provides yet another way to produce monochromatic light, one he felt was superior to other linear birefringent filters being developed at the time. He ingeniously isolated specific wavelengths of color by using quartz's ability to rotate the plane of light via a series of precision-cut basal sections of quartz sandwiched between polarizing filters as seen in Figure 8. Together with John L. Rosenfeld, he published a fascinating paper in the *American Mineralogist* entitled "Monochromator Utilizing the Rotatory Power of Quartz," freely available on the Mineralogical Society of America (MSA) website at http://www.minsocam.org/ammin/AM37/AM37_158.pdf (Hurlbut and Rosenfeld 1952). While extremely well-written and in a very accessible style, given its intended audience it assumes a certain advanced level of understanding of the underlying causes and effects of optical activity, yet at the same time it also contributes to that understanding. Now armed with insights into the bull's eye and having practical experience with it, one

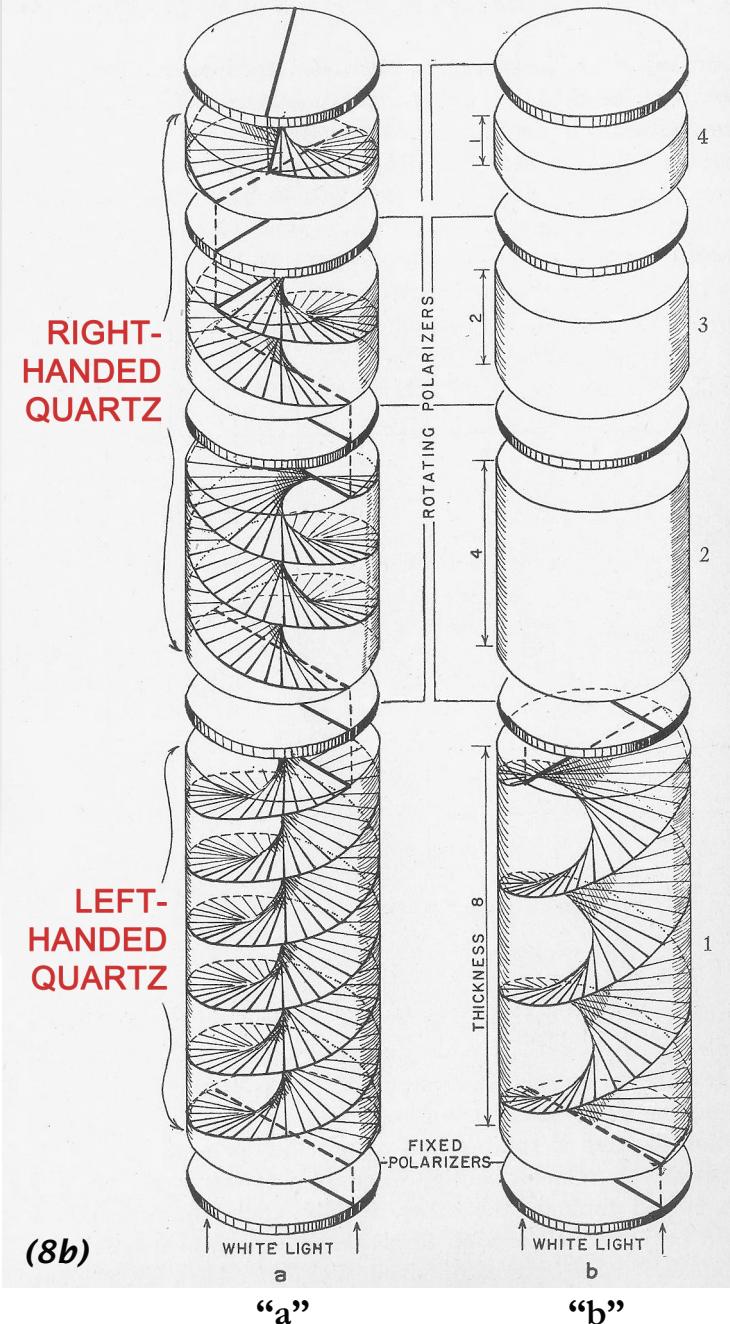
(continued on page 10)



(8a)

Figure 8a: The quartz monochromator is a *tunable filter* utilizing the rotatory power and large rotatory dispersion of quartz to provide monochromatic light of a specific narrow wavelength band of approximately 150 angstroms (15 nm). Turning the knob at its lower right moves the dial to the desired wavelength, the color of which then exits through the round window shown here at the top. The small knob next to the window adjusts the height of that end of the instrument when it is lying down as shown in Figure 9b. This hefty half pound instrument measures 15 cm high x 9 cm wide and 9 cm deep.

PLANE POLARIZED LIGHT
EMERGES AT THIS END



(8b)

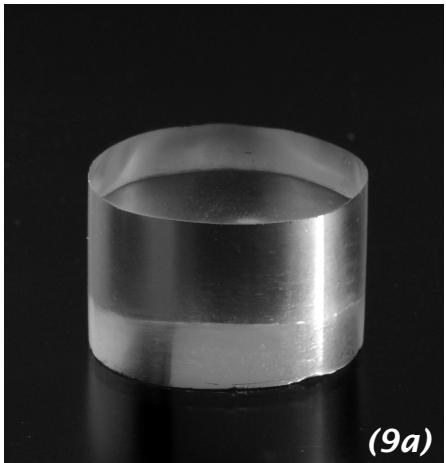
"a"

"b"

Figure 8b: Diagram "a" represents the quartz/polarizing filter arrangement oriented just as it is inside the monochromater, directly below the round window at the top of the image in Figure 8a. The first stage (lowest in the diagram) is a good illustration of the simple principle of rotation of plane polarized light within the cylinder of quartz from polarizing filter to polarizer to analyzer).

Diagram "a" shows the left-handed rotation (counter-clockwise) of short wavelength (high-frequency blue end of the visible spectrum) and diagram "b" shows the long wavelength (low-frequency red end of the spectrum); it is also blocked from going beyond the first thickest section by the position of the polarizer between the first and second sections. The second, third, and fourth stages simply take the range of wavelengths from the previous stage and further stretch it out until the light at the top covers a small range of wavelengths, i.e., is even more monochromatic. As the knob is rotated, the large dial also turns and indicates the wavelength being transmitted. As light passes through the system, each following stage eliminates half of the light entering it (see Fig. 9c).

The diagram's original optical handedness labels have been changed in order to be consistent with the point of view used in a polariscope (Fig. 3); that is, handedness is determined looking into the path of oncoming light (Hurlbut and Rosenfeld 1952, page 162; diagram courtesy of the Mineralogical Society of America).



(9a)

Figure 9a: A 14.75 mm thick basal section of quartz similar to those used within the monochromator; optically oriented by the author (EAS) and custom cut for this project by Mark Oros.

Figure 9c: A band of nearly monochromatic light is transmitted (approximately 150 angstroms bandwidth). In this example, the external dial has rotated the quartz and polarizing filter components until the emitted narrow band of color is roughly 520 nm green, as shown at right in the central image of the monochromator in use with fiber optic light (Hurlbut and Rosenfeld 1952, page 163; diagram courtesy of the Mineralogical Society of America).

(9c)

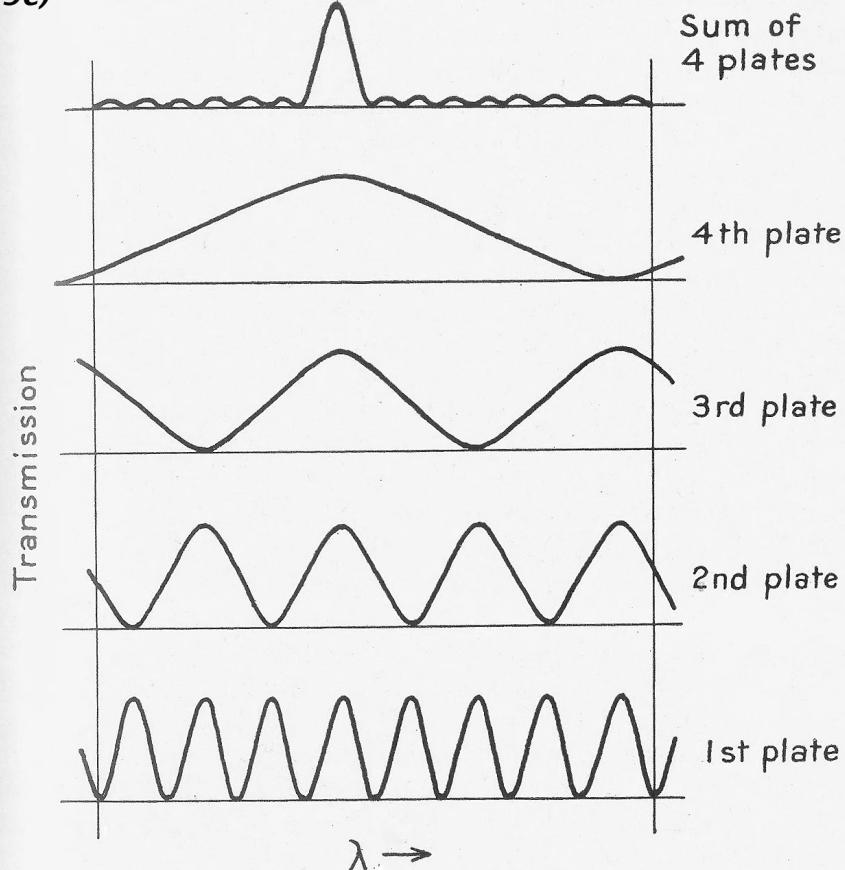


Figure 9b: Dialing in the desired wavelength turns the internal quartz/polarizing filter components simultaneously and monochromatic color ultimately exits the opposite side of the instrument from the light source (in this case a fiber optic light), captured here in a mirror placed at the rear of the instrument. From top to bottom at right: 450 nm violet, 470 nm blue, 520 nm green, 570 nm yellow and 650 nm red. The plane of the emerging wavelength is N-S so that it could be used with the polarizing microscopes in use in the United States at that time.

(9b)



450 nm



470 nm



520 nm



570 nm



650 nm

650 nm
Red Light

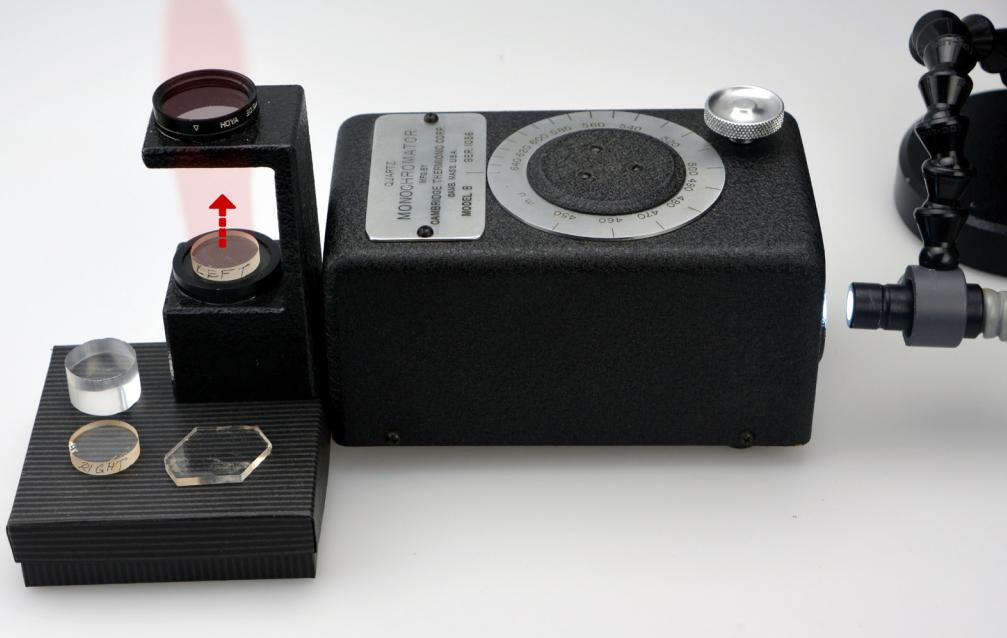


Figure 10: The narrow bandwidth of light generated by the quartz monochromator is useful in a number of applications. With the dial set to 650 nm, it is shown here selecting red light from the white light generated by the fiber optic source at far right. A portable polariscope with its rear light port lined up with the exit port of the monochromator directs the beam up through the polarizer, a 4 mm left-handed basal section of quartz and the upper filter to the viewer. By rotating the upper polar (analyzer) of the polariscope one can make refined observations of the optical activity in quartz specimens, including illustrating the values of Table 1 by noting how many degrees the analyzer must be turned for each wavelength of color listed. Pictured are the 3 mm and 14.75 mm thick basal sections shown earlier, along with two 4 mm thick basal slices, one each of left and right-handed quartz.

(continued from page 7)

gains an appreciation for just how elegant the design of the Hurlbut quartz monochromator is: a *tunable filter* utilizing the rotatory power and large rotatory dispersion of quartz to provide monochromatic light.

As explained earlier, shorter wavelengths are rotated more and longer wavelengths are rotated less; the specific amount is given in Table 1. The large rotatory dispersion of quartz is evidenced by the difference in extremes: if violet 400 nm light is rotated 49.0 degrees per millimeter and red 700 nanometer light is rotated only 15.3 degrees per millimeter, the difference between the colors is 33.7 degrees over one millimeter. This is the basis on which Hurlbut constructed the monochromator; employing relatively thick basal sections, because *the greater the thickness, the larger the separation of wavelengths*. Also, they are easy to handle (much thinner slices would also work, but are harder to cut and presumably the internal mechanical gearing would then be more difficult to implement).

What is more, since the rotatory power to separate the colors is the same for left and right-handed quartz, the choice of handedness for stage 1 and for stages 2, 3, and 4 in the monochromator does not matter. Given that each handedness occurs in roughly equal amounts in nature (hence any purchased lot will contain roughly equal amounts of each), it is logical to make the thickest section (53 mm) one half of the total four quartz sections and the remaining three sections of opposite handedness than the first. The thickness of each suc-

cessive section is half that of the one previous to it; a ratio of 1:2:4:8. There is a fixed polar at each end of the instrument while the remaining ones rotate with the quartz sections. The final polar is set in the N-S position in order to transmit N-S plane polarized light as was the convention in the United States for polarizing microscopes at the time (today the international convention is for it to be E-W). The inner filters are cemented to the quartz sections to minimize attenuation by interface reflection and mechanical gearing turns each proportionally and at the same time, all by using the knob on the front of the instrument. As the knob is rotated, the large dial also turns and indicates the wavelength being emitted. As light passes through the system, each following stage eliminates half of the light entering it (Fig. 9c). It is remarkable that the emergent narrow band of monochromatic light is approximately 150 angstroms (15 nm) and that this could be halved to 75 angstroms (7.5 nm) by using five quartz sections rather than the four of the present design.

In the Hurlbut paper, point of view and structural versus optical handedness is not stated. We have taken the liberty of relabeling the diagram in Figure 8b to be consistent with the convention which we have taken throughout the present paper, namely, handedness is determined looking into the path of oncoming light. Hurlbut's original diagrams reproduced in Figures 8 and 9 have expanded captions intended to illuminate ideas he and Rosenfeld outlined in their *American Mineralogist* paper.

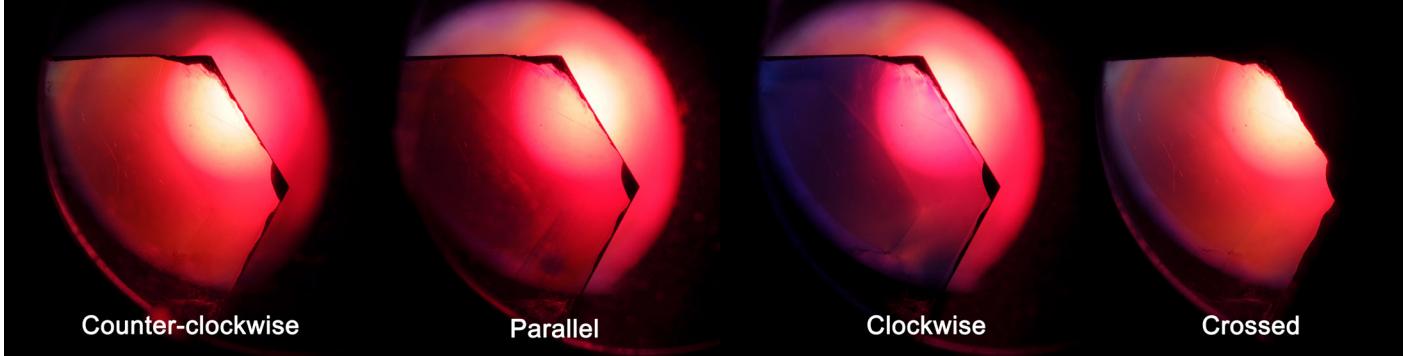


Figure 11: This perfect demonstration of rotatory power and rotatory dispersion also confirms the handedness of different quartz basal sections. Using a setup similar to that in Figure 10, another confirmation test for handedness of the 3 mm basal section of quartz was made using the monochromator. Using 650 nm light and starting with the polars in the parallel (open) position, turning the analyzer counter-clockwise makes the quartz brightest an angle consistent with Table 1; turning the analyzer clockwise makes the quartz darker. This confirms that the crystal is left-handed. The opposite reaction would have indicated right-handedness. Please note, the central yellowish color is an artifact of the digital camera's reaction to the fiberoptic light. It is actually red to the eye.

It is the hope of the present authors that “Quartz: a Bull’s Eye on Optical Activity” will bring greater awareness of this fine paper and fascinating instrument. Without doubt, this monochromator is an excellent illustration of putting into action the strong rotatory power and large rotatory dispersion of quartz as it “magically” produces individual colors from colorless crystal (Fig. 9b).

Epilogue

The authors have recently put the monochromator’s ability to produce a narrow band of monochromatic light to good use in a most appropriate manner: that of making direct determinations of handedness in our basal sections of quartz by selecting an appropriate wavelength from Table 1 (setup shown in Figure 10). We aligned the polars parallel, turned the analyzer first counter-clockwise, then clockwise while observing the intensity of the transmitted light (Fig. 11). Exercises such as this also help us to understand a related, earlier instrument which we have not yet had the opportunity to examine first-hand: the “Rotatory Dispersion Colorimetric Photometer,” developed by Irwin G. Priest in the early 1920s and constructed by O.G. Lang and H.C. Wundar, of the Bureau of Standards Instrument Shop. For a detailed description of this instrument, see “The Colorimetry and Photometry of Daylight and Incandescent Illuminants by the Method of Rotatory Dispersion” (Priest 1923).

Understanding the bull’s eye of quartz offers a rigorous workout for the mind and sheds light on just one of many riddles this complex mineral has to offer. Whether one is a collector, educator, student, lapidary or gemologist, the opportunity should not be missed to explore this intriguing optical phenomenon and to share it with others.

Acknowledgments

Elise Skalwold would like to thank her co-author Dr. William A. Bassett, Dr. Mickey Gunter, and Dr. Olaf Medenbach all for years of insightful and inspirational dialogue surrounding optical mineralogy. Additionally, we would like to thank Dr. J. Alexander Speer, Executive Director of the Mineralogical Society of America, for granting permission to reproduce the essential diagrams from the *American Mineralogist* 1952 Hurlbut and Rosenfeld paper. Many thanks to James H. Edwards and Betty & David N. Kobernuss, Sr. for careful copy-editing and to Dr. Carl A. Francis, Dr. John Rakovan, *Rocks & Minerals* Editor-in-Chief Marie E. Huizing and Smithsonian National Mineral and Gem Collection Emeritus Curator-in-charge John S. White for their enthusiastic encouragement to publish this paper. Finally, our sincere appreciation to Dr. Olaf Medenbach for careful review of the manuscript and for providing suggestions for improvement.



Figure 12: Quartz basal sections and crystals. The two 4 mm thick slices in the foreground were a gift to the author (EAS) from mineralogist Dr. Olaf Medenbach for this project. The 3 mm slice with intact prism faces was a gift from her co-author (WAB).



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Left: A prismatic synthetic quartz crystal, Russian, 7 x 100 mm.

Elise A. Skalwold is an Accredited Senior Gemologist and author involved in research and curating with her co-author at her alma mater, Cornell University (B.Sc. 1982). Her primary interests are inclusions, optical mineralogy, and crystallography. Currently serving as Consulting Gemological Curator in the Earth and Atmospheric Sciences Department, she is a Graduate Gemologist (GG), trained in residence at the Gemological Institute of America (GIA) Robert Mouawad Campus located in Carlsbad, California. While living in Thailand she worked in the famous gem markets of both Chanthaburi and Bangkok and pursued studies at the Gem & Jewelry Institute of Thailand (at that time part of Chulalongkorn University) for which she was subsequently elected a Fellow of the Gemmological Association of Great Britain (FGA). She is an active member of the Society of Mineral Museum Professionals (SMMMP), a world-wide network linking curators from large and small institutions from which members draw on combined expertise.

As well as having co-authored with Dr. Bassett the 415 page book *The Edward Arthur Metzger Gem Collection* and presently working on a companion volume to it, Ms. Skalwold is an author/co-author of gemology and mineralogy papers featured in *InColor, Gems & Gemology, The Journal of Gemmology* and *Rocks & Minerals*. The 2014 article “The Microworld of Diamonds: Images from Earth’s Mantle,” co-authored with world-renowned photomicrographer and gemologist John I. Koivula, recently won the 2014 Best Article of the Year Award for the prestigious publication *Rocks & Minerals*. She serves as Contributing Editor for “G&G Micro-World” (a quarterly column exploring inclusions found in minerals and other gem materials) which premiered in the Summer 2015 issue of *Gems & Gemology*, the peer-reviewed scientific journal of the GIA.

Passionate about gemology, she is actively involved in bringing this science into a university setting for the benefit of students and non-students alike – this is the quintessential theme of her paper “Scholarly Treasure: The Role of Gems in a University Setting,” presented at the 2013 GIA-sponsored first-ever Gemological Session of the Geological Society of America (GSA) 125th Anniversary Annual Meeting. Her speaking engagements have recently included the New York Mineralogical Club (co-founded by George F. Kunz in 1886), the 40th Annual Rochester Mineralogical Symposium and the 11th Annual Sinkankas Symposium [Ruby] held at the Gemological Institute of America in Carlsbad, California.

Meet the Authors



The authors prepare the teaching cart for visitors of the Timothy N. Heasley Mineralogy Museum in the Earth & Atmospheric Sciences Department, Snee Hall, Cornell University.

William A. Bassett, PhD, is Professor Emeritus in the Department of Earth and Atmospheric Sciences, Cornell University, where he taught courses in mineralogy and crystallography. After receiving his PhD in Geology in 1959 at Columbia University he conducted research in geochronology in the Department of Chemistry at Brookhaven National Laboratory. In 1961 he took a position as Professor of Geology at The University of Rochester where he conducted research to determine the properties of materials at high pressures and temperatures to provide a means for a better understanding of the composition and physical characteristics of minerals in the Earth’s interior. In 1978 he joined the Department of Geological Sciences (later to become the Department of Earth and Atmospheric Sciences) of Cornell University where he studied not only the properties of minerals, but analyzed specimens brought to the surface from deep within the Earth’s interior.

As well as being one of the pioneers of diamond anvil cell (DAC) high pressure research, in 1994 Dr. Bassett received the Roebling Medal for his work in mineralogy; the highest award of the Mineralogical Society of America for scientific eminence as represented primarily by scientific publication of outstanding original research in mineralogy. He received the Bridgman Award, given by the International Association for High Pressure Research and was awarded a Guggenheim fellowship for study abroad. He has been a visiting professor at the University of Paris, MIT, and Brigham Young University.

Since retirement in 2000 he continues to serve Cornell as Curator of Geologic Collections. As one of the founding members, Board Chairman, and Advisory Board member of the Sciencenter of Ithaca, he has contributed to the designing and building of exhibits and the many other hands-on experiences offered to visitors young and old. Today he continues his research in high-pressure studies and makes diamond anvil cells for sale to high pressure-temperature researchers the world over.

As both a witness to and a participant in the long history of the diamond anvil cell and the impact which it continues to have, Dr. Bassett was invited to share his insights into this unique instrument with his 2009 paper “The Diamond Anvil Cell, 50th Birthday,” published in *High Pressure Research*, 29, 163-18 and freely available at: <http://www.compres.us/files/bassett/50%20Years%20DAC%20Hist.pdf>.



Published by the Mineralogical Society of America, Chantilly, Virginia, USA

ISBN: 978-0-939950-00-3