## This is the story of conical refraction that was discovered more than 150 years ago and only now will come to real first applications.

It took us more than 150 years to see what Hamilton predicted as theory in 1832 at the Royal Irish Academy and Lloyd proofed by experiment in the same year. Even when he was young William Hamilton was one of the best scientists of his days. He was active as well in astronomy where he got his professor, as in mathematics and physics. Between 1827 and 1833 Hamilton published a series of papers in the *Transactions of the Royal Irish Academy*. It was a sensation when in 1832 he predicted the optical effect of both internal and external conical refraction, which shortly after was experimentally proofed by Rev. Humphrey Lloyd, fellow of Trinity College and professor of natural and philosophy in the university of Dublin.

The phenomenon of conical refraction is very unique and is based on the double refraction behaviour of biaxial material. At internal conical refraction a regularly unpolarized or circular polarized light beam of small divergence and diameter is incident along the binormal of a biaxial crystal whereby the outgoing beam profile looks like a hollow cylinder of light. The binormal is an axis which lies between two crystallo-optical axes.

In the case of external conical refraction we talk about the biradial, which also lies between two crystallo-optical axes. Light is focussed with a well defined cone angle onto the entrance facet of the crystal whereby a so called beam filamentor is build. This means that the beam will pass the crystal along its biradial with the diameter of the focus spot.

Just behind the exit facet the beam will spread into a hollow light cone, with the same angle of cone as the focussed beam in front of the entrance facet.

The question now is, how it is possible that Lloyd managed to make this experiment more than 150 years ago and that up to today this effect, which even is described in several papers and also some books of physics, is not demonstrated to millions of students and without applications. The answer is easy and also nearly a tragedy. Lloyd managed to get some biaxial material for his experiment that was grown by nature but that is so rare that later generation had no chance to repeat what he did.

It has to be mentioned that for realization of this effect it is not sufficient to have a biaxial medium. The additional special demands to such a medium are a steady undisturbed molecular structure without impurities, high optical transparency, a dispersion-free optical non-active binormal/biradial, parallel end facets which are, in the best case, perpendicular to the binormal/biradial, acceptable thermo-mechanical properties, chemical stability and relatively high optical refraction of all three crystallo-optical axes, where the refraction indices must have very equidistant values. Further on the optical path length along the binormal should have a minimum length of 15 mm in order to be able to see and measure the effect clearly.

For his experiment Lloyd has used a crystal of formula $CaCO_3$ named aragonite. Now many people will say that they know this stone and even can tell where to buy in big quantity. But for this experiment the crystal has to fulfil all the above mentioned demands and therefore quite all worldwide existing aragonite crystals are not useful for this effect of conical refraction, except the aragonite from Hamilton and Lloyd and about one or two further aragonite crystals. The only known place where you can find suitable aragonite crystals for facets is in Horenec at Bilina in the Czech Republic. But nevertheless these crystals are not suitable for conical refraction. One reason is that they are too small, i.e. their weight is mostly lower than 100 ct, what means that it is not possible to obtain a required minimum crystal length of about 15 mm.

This is the reason why this experiment could not be repeated all the years, as aragonite crystals cannot be grown synthetically.

*Fig. 1 .: Aragonite,*
*Found in Horenec at Bilina,*
*Czech Republik*
*(http://www.natur.cuni.cz/~mineral/mineral/aragonit.html)*

*Fig. 2: Aragonite, length: 4 cm. Collection from the national museum in Prag, Czech Republik (http://www.natur.cuni.cz/~mineral/mineral/aragonit.html)*

*Fig. 3: Polished aragonite, weight: 52 ct, Czech Republik (http://www.volny.cz/gems)*

In 1832 Lloyd first time observed internal and external conical refraction with a specimen of aragonite, obtained from the company Dollond in London, and proved the theory of Hamilton with the set up from fig. 4. Although the parallel end facets of the aragonite were not perpendicular to the binormal (at internal conical refraction) and biaxial (at external conical refraction) and the optical path length of the crystal only was 12 mm, Lloyd managed to watch the effect.

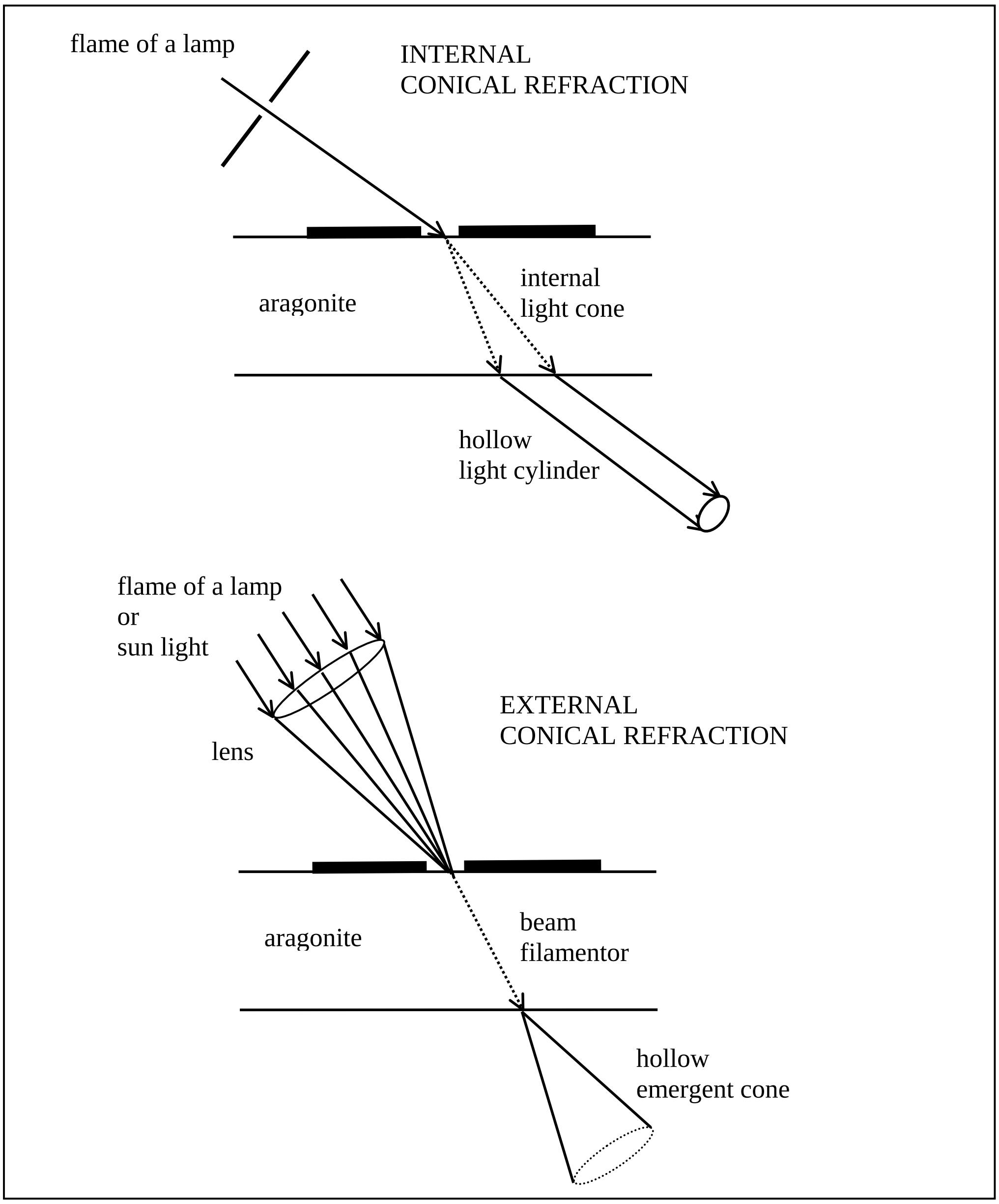


*Fig. 4: Experimental set up of Humphrey Lloyd to watch internal and external conical refraction*

Up to today there exists no way to grow this crystal synthetically and by this reason the effect of conical refraction was dammed to exist only as fundamental theory on paper.
During all the years some more types of crystals, with which conical refraction theoretically could be obtained, were found or developed. But not one of them could really fulfil all required parameters and properties to realize, measure and visualize this effect.
In January 2004 laser engineers of the company *Vision Crystal Technology AG (VCT AG)* in Germany first time demonstrated in their laboratories a standard set up to show easily both internal and external conical refraction with monoclinic double tungstate (MDT) crystals of formula $KY(WO_4)_2$. These crystals and other types of MDT- crystals are grown, oriented and cut by specialists of the *Vision Crystal Technology AG*.
External conical refraction is realized when the light cylinder, resulting from the internal conical refraction, is focussed with a certain angle of cone into a second crystal, which in comparison to the first crystal is rotated about 180° in the horizontal plane.
The engineers of the *VCT AG* used a HeNe-Laser in their set ups, because monochromatic light with a low $M^2$ -value and a small beam diameter leads to the best results.

The hollow light cylinder from the internal conical refraction strictly speaking consists of a hollow light cylinder, which additionally contains a second light cylinder of smaller diameter and less intensity. If these two interlocked cylinders hit a screen, one can see two light rings, separated by a dark ring, which was first time described and seen by J.C. Poggendorff in 1839. Therefore this dark ring is called Poggendorff ring. The size of the Poggendorff ring depends linear on the crystal length. The *VCT AG* uses a 20 mm long MDT- crystal, which leads to a Poggendorff ring diameter of about 0.9 mm behind the exit facet. After magnification with a lens and projection onto a screen, one gets a clear image of the ring pattern (fig. 7).
As for realization of conical refraction regularly unpolarized or circular polarized light is required, the polarized HeNe- laser beam is changed into a beam with circular polarization by passing a λ/4- plate. After that the beam is tightly focussed by a lens in front of the entrance facet of the crystal, where the beam diameter is about 200 µm. In this case the Raleigh length of the focussed beam is larger than the crystal length itself. This is necessary because the ring pattern, caused by internal conical refraction, can only be visualized when the incoming beam is with low divergence.

**Conical Refraction, realized by engineers of the VCT AG:**

Internal conical refraction:

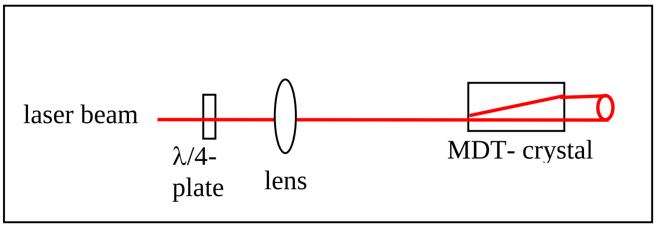


*Fig. 5: Modern set up for internal conical refraction*

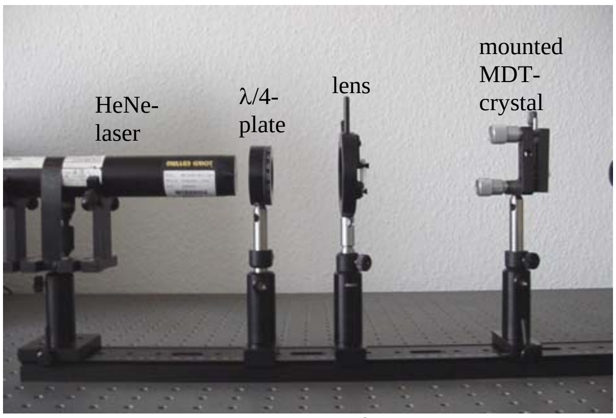


*Fig. 6: Experimental set up for internal conical refraction*

*Fig. 7: Magnified and on screen projected light- and Poggendorff rings, resulting from internal conical refraction with a 20 mm long MDT- crystal of the VCT AG.*

External conical refraction:

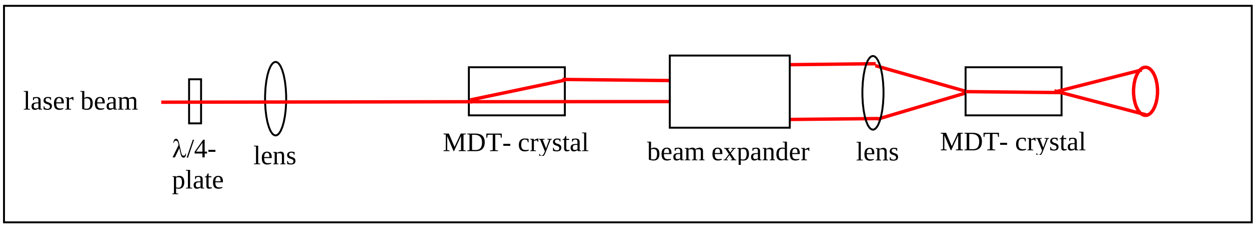


*Fig. 8: Modern set up for external conical refraction*

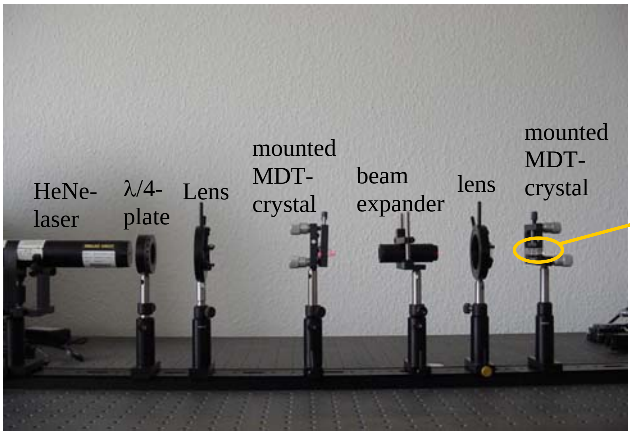


*Fig. 9: Experimental set up for external conical refraction*

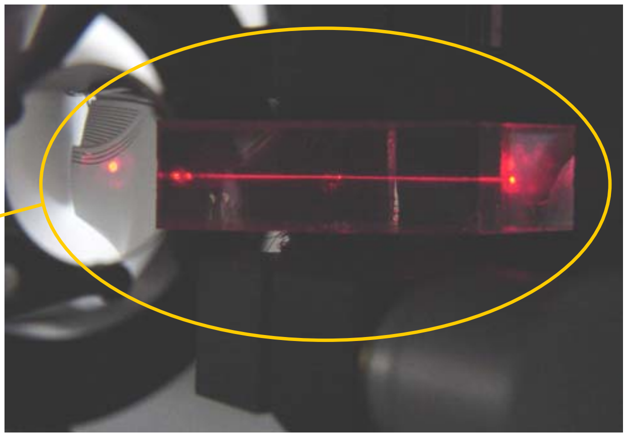

*Fig. 10: Beam filamentation, resulting from external conical refraction, within a MDT- crystal, grown, cut and polished by specialists of the VCT AG*

In parallel to all practical experiments the engineers of the *VCT AG* are working to confirm the theories of A. M. Belsky and M. A. Stepanov who published some key papers [1, 2, 3] about mathematical models on internal conical refraction within the last three years.
The team of the *VCT AG* is sure that conical refraction quickly will find the way to real applications and that this nearly forgotten effect will boost many areas of laser technology.

As first serial product of conical refraction the *VCT AG* has introduced ready orientated, cut and polished MDT-crystals as well as complete education kits for both internal- and external conical refraction.
That means from today on students will have a chance to see what Humphrey Lloyd has seen more than 150 years ago .
Additionally there are many possible future applications of this effect, not at least because of the existence of laser beam sources.
With help of internal conical refraction a Gaussian beam profile could be transformed into a “flat-top” beam profile or into a Bessel beam.
The hollow light cylinder could be used as optical tweezers with very special properties.
Also novel interference patterns with local shiftings could be generated and a very promising application would be a real depolarizer, only consisting of two short crystal elements, which are fixed in a well defined orientation to each other. This depolarizer can also be taken to generate speckle free illuminations and interference patterns, what is interesting for holographic applications.
In case of external conical refraction non-linear effects could be achieved very easily as the explained beam filamentation (fig. 10) enables a constant high intensity density within the crystal and requires comparatively low input powers. For example it would become possible to achieve stimulated Raman scattering with a cw- instead of a pulsed input beam.

Also Kerr lens mode locking with low input powers and effects based on phase conjugations could become future applications.
Let's thank Hamilton and Lloyd for their brilliant scientific work in the past.


[1] A. M. Belsky, M. A. Stepanov, Internal conical refraction of coherent light beams, *Optics Communications*, vol. 167 (1999), pp. 1-5

[2] A. M. Belsky, M. A. Stepanov, Internal conical refraction of Bessel light beams, *Optics and Spectroscopy*, vol. 92, no. 3 (2002), pp. 455-458

[3] A. M. Belsky, M. A. Stepanov, Transformation of Bessel beams under internal conical refraction, *Optics Communications, vol. 212 (2002), pp. 11-16*


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Vorgelegt von der


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